2025-03-31

Application

Draft **Brandenburg, Axel**

Information about applicant

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Information about application

Call name: Research Grants Open call 2025 (Natural and Engineering Sciences)

Type of grant: Research Project Grant

Focus: Natural and engineering sciences

Call for proposals subject area: NE

Project title: Probing the first microseconds of the Universe with magnetic fields and gravitational waves

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Project end: 2028-12-31

Review panel applied for:

Classification code: 10305. Astronomy, Astrophysics and Cosmology

Keywords: cosmology, magnetic fields, turbulence, reconnection, radiation transport

Descriptive information

Project information

Project title (Swedish)

Undersöka de första mikrosekunderna av universum med magnetfält och gravitationsvågor

Project title (English)

Probing the first microseconds of the Universe with magnetic fields and gravitational waves

Abstract and popular science description

Abstract (English)

Popular science description (Swedish)

Planned use of research infrastructure

Specify national/international infrastructures funded by the Swedish Research Council, not local core facilities.

Planned use of research infrastructure

Yes

Research infrastructure/s

NAISS - National Academic Infrastructure for Supercomputing in Sweden

Other research infrastructure

Other applications and grants

Describe if any of the items below are relevant to you.

- You are applying for or intend to apply for other grants from the Swedish Research Council.
- You are receiving an ongoing grant from the Swedish Research Council with a grant period that wholly or partly overlaps with the grant you are now applying for.
- Applications or grants relating to the same project idea from the Swedish Research Council or other funding bodies (from you or another researcher).

If you answer Yes, you should, in all cases, justify why you submit one or more applications and also describe the relationship between the different projects.

Are any of the items relevant to you?

No

Research description

Ethical aspects: Legal and formal requirements

State the specific legal and formal requirements that may be relevant for your application.

The research includes experiments on animals that requires ethical approval under the Animal Welfare Act (2018:1192)

No

The research includes studies on humans and/or biological material from humans and requires approval under the Act (2003:460) on ethical review of research relating to humans

No

The research includes the processing of personal data in accordance with the General Data Protection Regulation

No

If you answered Yes to one or more of the questions above, you should describe how you plan to obtain relevant approvals and permits before the project starts.

Regardless if you answered Yes or No to the questions above, state whether other approvals or permits, in addition to the above, are relevant to your application. If no approvals or permits affect you application please, state this.

Description of approvals and permits (English)

not applicable

Ethical considerations

Specify any ethical issues raised by the project (or equivalent) and describe how they will be addressed, according to the guidelines in the call text. If no ethical issues are raised, justify this.

Description of ethical considerations (English)

not applicable

Sex and gender dimensions

Please state whether sex and gender dimensions are applicable in your planned research, and justify your decision, according to the instructions in the call text.

Sex and gender dimensions in the proposed research

No

Justification of answer (English)

not applicable

Research plan

Research plan (English)

See following page for attachment

Appendix A: Research plan Axel Brandenburg (590407-8317)

1 Purpose and aims

Our Universe is well modeled by the theory of cold dark matter (CDM) with a non-vanishing integration constant, the Λ term in Einstein's equations, responsible for the accelerated expansion of the Universe over the past billion years. The *observational foundations* of the ΛCDM model rest upon three major pillars related to the epochs of Big Bang nuclear synthesis (when the Universe was ~ 15 minutes old), the cosmic microwave background (which formed when the universe was 400,000 years old), and the expansion history and large-scale structure of the Universe observed today. The major goal of this project is to help establishing a probe of the first microseconds of the Universe using magnetic fields and gravitational waves.

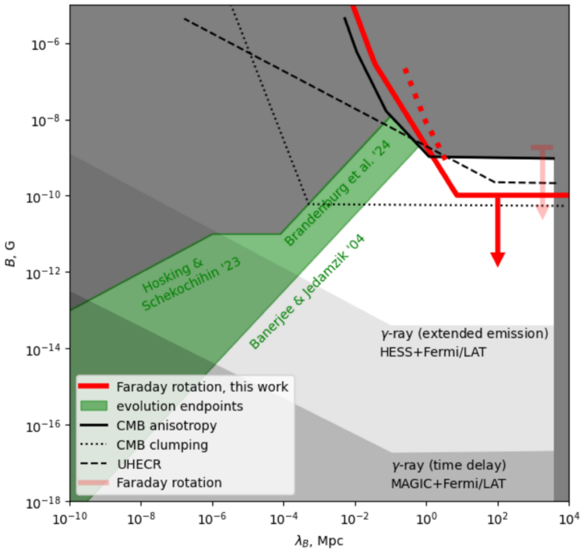

Figure 1: Primordial magnetic field limits B versus length scale λ_B obtained through the combination of radio and γ-ray observations of the low red shift universe, combined with advanced modeling of the evolution of magnetic fields with cosmic structures. Taken from Neronov et al. (2024).

Primordial magnetic fields are routinely described in a diagnostic diagram of comoving field strength B versus comoving length scale λ_B; see Figure 1. Using the non-observation of extended and delayed secondary γ-ray emission from distant extragalactic sources such as active galactic nuclei (Neronov & Vovk, 2010; Acciari et al., 2023) and γ-ray bursts (Vovk et al., 2024), lower limits on B were previously obtained. Upper limits are now provided through residual rotation measures obtained from LOFAR Carretti et al. (2025).

Using numerical simulations, we will be able to use magnetic fields to trace back their origin to the epochs of inflation, or the electroweak (EW) or quark confinement (or QCD) phase transitions (PT). In addition, we will use the stochastic gravitational wave background to established a connection between the present day observed magnetic field and its possible source at one of the epochs in the early universe. Already now, pulsar timing array observations in the nHz range have traced their origin to the epoch of quark confinement (Brandenburg et al., 2021; Roper Pol et al., 2022). Higher frequencies in the mHz range will be available in future through Laser Interferometer Space Antenna (LISA).

Based on theory, we know that all magnetic field models have the endpoints on a unique line (Banerjee & Jedamzik, 2004; Hosking & Schekochihin, 2023; Brandenburg et al., 2024), although there are still some differences in their precise position; see Figure 1 from the work of Neronov et al. (2024). A particular point on this line has been identified by Jedamzik et al. (2025b), who showed that the Hubble tension (the 5σ discrepancy between the value of the Hubble constant of $67.36\,\mathrm{km/s\,kpc}^{-1}$ from Planck and $73.04\,\mathrm{km/s\,kpc}^{-1}$ from the SH0ES collaboration using type ia supernovae) can be alleviated by density enhancements caused by a primordial magnetic field of $5\,\mathrm{pG}$ at a scale of $\approx 1\,\mathrm{kpc}$. This is referred to as baryon clumping. A connection between the point $(B, \lambda_B) = (5\,\mathrm{pG}, 1\,\mathrm{kpc})$ of Jedamzik et al. (2025b) and the PTA data suggesting $(B, \lambda_B) = (1\,\mu\mathrm{G}, 0.1\,\mathrm{pc})$ can indeed be explained by a non-helical magnetic field evolution when $B \propto \lambda_B^{-5/4}$; see Hosking & Schekochihin (2023). This is shown in Figure 2.

To be able to compute the amount of baron clumping at recombination and the field strength and coherence length today, we need to take into account the detailed ionization history and radiation dynamics at the time of photon decoupling from the matter, which occurs shortly before the epoch of recombination. As the photon mean-free path increases, the dissipation changes from a diffusion of particles at small mean-free path to a regime of drag from the free-streaming photon background. This leads to the magnetic field being frozen into the plasma. The overall purpose of this project is therefore:

- to study the magnetic field evolution near the time of photon decoupling,
- to assess the magnetic field level when it becomes frozen into the plasma, and
- to compute the effects of the magnetic field on the cosmological evolution.

The latter topic is crucial for addressing the Hubble tension and other discrepancies between the late and early evolution of the Universe; see Jedamzik & Pogosian (2020) and Jedamzik et al. (2025a).

A major realization of the last few years was the discovery of what is now called the Hosking integral, a new conserved quantity. It is the correlation integral of the magnetic helicity variance and governs magnetically dominated turbulence in previously unknown and surprising ways. The basic idea is that magnetic helicity, while it may be vanishing on average, it is always finite in patches. The relevant conserved quantity is the Hosking integral (Hosking & Schekochihin, 2021). As already alluded to in the beginning, their subsequent work (Hosking & Schekochihin, 2023) also makes another remarkable claim, namely that the overall decay time τ of the magnetic energy density is not only governed by the decay exponent, but also by the timescale, which, if expressed in terms of the instantaneous Alfvén time τ_A, depends on the microphysical magnetic resistivity. This is quantified by the coefficient C_M in the relation $\tau = C_\mathrm{M}\tau_\mathrm{A}$. From a hydrodynamic point of view (no magnetic fields), this would be unexpected, because hydrodynamic turbulence is known to be independent of the microphysical viscosity. This is a basic assumption underlying the applicability of large eddy simulations, which may thus not be correct in the presence of strong magnetic fields.

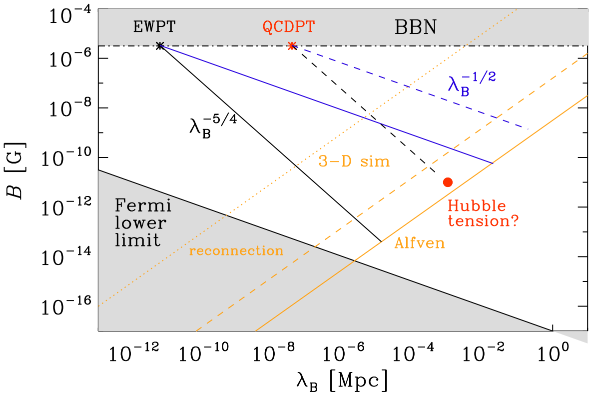

Figure 2: Decay of a nonhelical magnetic field $B \propto t^{-5/9}$ with conformal time t and growth of the magnetic length scale $\lambda_B \propto t^{4/9}$ corresponds to an evolution $B \propto \lambda_B^{-5/4}$ in a diagram showing B versus λ_lambda_B (black lines). The asterisks denote the start of the evolution from the electroweak phase transition (EWPT, black) or the QCD phase transition (QCDPT, red), with the maximally allowed value for B to not affect the rate of neutron β-decay, which would affect the ^{4}He abundance during big bang nucleosynthesis (BBN). The evolution stops at one of the orange lines; which one is subject to the present proposal. The solid line corresponds to Alfvén scaling (assumed in Banerjee & Jedamzik, 2004), the dotted line applies if the decay is constrained by reconnection with a large magnetic Prandtl number (assumed in Hosking & Schekochihin, 2023). The dashed line is the result of preliminary numerical investigations in 2-D (Brandenburg et al., 2024). The blue line corresponds to helical decay. The red point marked with ‘Hubble tension?’ refers to what might be needed to alleviate it.

In magnetohydrodynamics (MHD), the strength of a turbulent magnetic field with a root-mean-square (rms) magnetic field B_rms is characterized by the Alfvén speed, $v_\mathrm{A} = B_\mathrm{rms}/\sqrt{\mu_0\rho_0}$, where μ_0 is the permeability and ρ_0 is the density. The resistivity or magnetic diffusivity η is then quantified by the Lundquist number $\mathrm{Lu} = v_\mathrm{A}/\eta k_0$, where k_0 is the peak wavenumber of the magnetic energy spectrum. Our preliminary work confirms a resistive dependence of the decay time, but leaves important questions still answered. Can we trust the numerics,

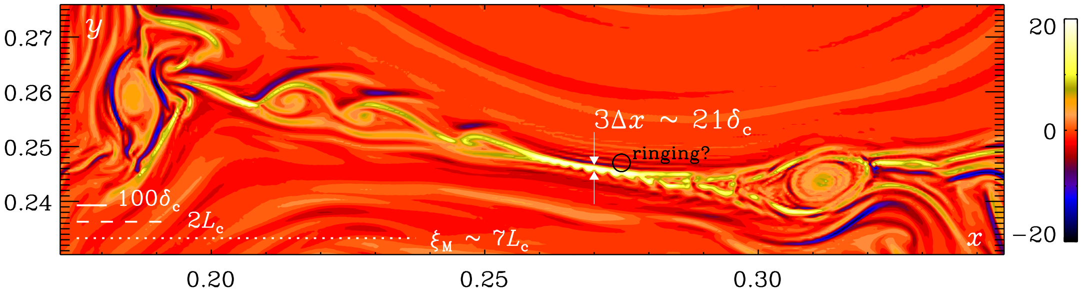

Figure 3: Zoom-in of a small piece of a 2-D simulation of decaying MHD turbulence showing a current sheet (yellow) breaking up into little islands (plasmoids). Yellow (blue) tones correspond to positive (negative) values of the normal component of the current density in a simulations with $\mathrm{Pr}_M = 10$ using 16384^2 mesh points over $(2\pi)^2$. The lengths of $100\,\delta_\mathrm{c}$, $2L_\mathrm{c}$, and λ_B are indicated by horizontal white solid, dashed, and dotted lines, respectively. The thickness of the current sheet corresponds to about $3\Delta x \approx 21\,\delta_\mathrm{c}$, where Δx is the mesh spacing. In its proximity, there are also indications of ringing, indicated by the black circle. Adapted from Brandenburg et al. (2024).

especially when the magnetic Prandtl number (Pr_M, i.e., the ratio of microphysical viscosity to microphysical magnetic diffusivity) is large? A Pr_M-dependence is found in driven magnetic reconnection (Comisso et al., 2015), where a single current sheet of length L_c and thickness δ_c is seen to break up into smaller ones due to the production of plasmoids. In our 2-D simulations of turbulent decay, we also see plasmoid production; see Figure 3.

But reconnection is an idealized experimental setup that may not have much to say about turbulence. In particular, in decaying turbulence simulations, reconnection sites are intermittent in time and space and are not volume-filling, so their role may not be very important. We will therefore carry out carefully designed control experiments, focusing on possible artifacts from finite domain sizes. Earlier work of Hosking & Schekochihin (2021) has claimed to be able to take advantage of using hyperviscosity and hyperresistivity, but there are concerns about side effects. It is therefore important to reconsider the possibility of artifacts. Here, we will instead perform full radiation-hydrodynamic simulations.

Around the epoch of recommendation, i.e., near the end of the radiation dominated era, the photon mean-free path becomes very long and introduces damping of the velocity field. This effect has been examined in earlier work (Banerjee & Jedamzik, 2004; Hosking & Schekochihin, 2023), but this was only done in an approximate way. Here, we will produce very large resolution simulations where we introduce and study this effect on the decay law. Simulations with coupling to the photon field are also important for alleviating the Hubble tension by lowering the sound horizon through magnetically produced density clumping (Jedamzik & Pogosian, 2020; Jedamzik et al., 2025a).

An important aspect of all future simulation is the utilization of graphics processing units (GPUs). For that purpose, we will also utilize the Large Unified Modern Infrastructure LUMI in Kajaani (Finland); see Pekkilä et al. (2022) for relevant code development relevant for the PENCIL CODE (Pencil Code Collaboration, 2021). In summary, to accomplish the goals outlined in this proposal, our specific aims are as follows.

- Determine the scaling of MHD turbulence decay with Lundquist and magnetic Prandtl numbers. Assess artifacts resulting from finite domain size and finite resolution.
- Is there evidence for a saturation of the Lundquist number dependence of C_M in 3-D? This has so far only been seen in 2-D simulations, so new high-resolution 3-D simulations at 8192^3 mesh points may already suffice to demonstrate the saturation in 3-D simulations. Compare 3-D with

2-D and 2.5-D simulations, where the magnetic field has a component out of the plane.

- Is it true that C_M is independent of Pr_M? How does the answer to this question depend on numerical aspects such as the resolution, the range of Pr_M, i.e., can we expect and see a dependence already in the range 1–10, or do we need to go to the range 10–100, or even larger?
- What is the physics of the Lundquist number dependence at small values of Lu and of the saturation phenomenon? Is it related to the physics of reconnection? But if so, why is there no dependence of C_M on Pr_M, if it is indeed true that there is no such Pr_M-dependence in the decay of magnetic turbulence?
- Are there differences to forced reconnection experiments, where a dependence on Pr_M has been obtained (Comisso et al., 2015) and tentatively been reproduced (our preliminary work)?
- Consider the effects of radiative damping, which is relevant to the time of recombination. Check numerical restrictions regarding the number of rays and the efficiency of correction factors that were found to be useful in radiative cooling calculations in 2–D.
- Compared to earlier approximate treatments in terms of photon viscosity in the optically thick regime, and photon drag in the free-streaming regime, how important is a proper treatment of radiation to describe the effect of photon damping near the epoch of recombination? Is its functional form analogous to that of radiative cooling (Barekat & Brandenburg, 2014), where we know the answer and have included it routinely in simulations?

All these aims are compatible with past research experience of the PI, as demonstrated by his papers, especially in the last few years.

2 State of the art

In a recent paper (Brandenburg et al., 2024), we have computed the decay and Alfvén times as $\tau = (\mathrm{d}\ln v_\mathrm{A}^2/\mathrm{d}t)^{-1}$ and $\tau_\mathrm{A} = \lambda_B/v_\mathrm{A}$, and related them through $\tau = C_\mathrm{M}\tau_\mathrm{A}$. Here, λ_B is the integral scale of the turbulence, i.e., the inverse wavenumber of the peak of the spectrum, and v_A is the Alfvén speed. Our 3-D data points show an increase of C_M with Lu for small values of Lu. The C_M dependence on Lu is qualitatively similar for 2–D and 3–D turbulence. Moreover, the 2–D data points show that it becomes shallower for larger values of Lu. There is now evidence for C_M to level off and to become independent of Lu.

Reconnection has been studied for a very long time starting with the seminal works of Sweet and Parker, and then Petschek in the 1950s and 1960s. Much of our knowledge is derived from 2-D simulations. We know, for example, that current sheets develop that have a length $L_\mathrm{c} = \mathrm{Lu}_\mathrm{crit}\,\eta/v_\mathrm{A}$, where $\mathrm{Lu}_\mathrm{crit}$ is the critical value of the Lundquist number above which the plasmoid instability sets in, and $\delta_\mathrm{c} = L_\mathrm{c}/\mathrm{Lu}_\mathrm{c}^{1/2}$ is its thickness (Uzdensky, 2010). However, the possible connection to the decay of MHD turbulence is not at all obvious. A priori, one might have thought that, analogously to hydrodynamic turbulence, the decay time τ is just given by the dynamic or Alfvén time scale $\tau_\mathrm{A} = \lambda_B/v_\mathrm{A}$. This was assumed in the work of Banerjee & Jedamzik (2004). However, it now turns out that this is indeed too naive and now we know that τ and τ_A are related to each other through a prefactor, i.e., $\tau = C_\mathrm{M}\tau_\mathrm{A}$. This was suggested based on analogies with reconnection; see Hosking & Schekochihin (2023) for the details of this idea. An alternative idea is that the slow-down of the turbulent decay is related to magnetic helicity conservation. Here, we have to remember that the idea of the Hosking integral is, again, that magnetic helicity is conserved, but now only in smaller subvolumes. Thus, it is reasonable to expect a connection between the two.

At the end of photon decoupling, our simulations automatically produce density inhomogeneities. This has previously been studied separately, where the resulting baryon clumping enhances the recombination rate. This results in an earlier recombination and a subsequent reduction of the size of the cosmic sound horizon. This, in turn, alters the positions of the peaks of the cosmic microwave background (CMB) temperature spectrum and changes the estimate of the expansion rate of the Universe, given by the Hubble parameter H_0 from CMB data (Jedamzik & Pogosian, 2020; Jedamzik et al., 2021). This is particularly relevant in the context of one of the hottest topics in cosmology nowadays, i.e., the tension between the measurements of H_0 from CMB and low-redshift probes (Di Valentino et al., 2021; Kamionkowski & Riess, 2022). Accounting for magnetically-induced baryonic clumping may alleviate this tension (Jedamzik & Pogosian, 2020; Galli et al., 2022). The Hubble tension could thus hint at the presence of a primordial magnetic field during recombination. Our models may provide a self-consistent description of the coevolution of magnetic fields with the primordial plasma, to test the presence of a magnetic field at recombination and its influence on the CMB observables.

As with most observed phenomena in astrophysics, there can be multiple explanations that need to be kept in mind. Regarding the Hubble tension, another important contender—also studied at Nordita—is the idea that the sound horizon is lowered by the injection of energy from a phase transition in the dark sector Niedermann & Sloth (2021). Regarding intergalactic magnetism, an important contender is outflows (Aramburo-Garcia et al., 2022). However, recent work by Tjemsland et al. (2024) shows that their filling factors are likely insufficient to explain the observations. Finally, regarding the stochastic gravitational wave background, other known sources include supermassive black hole mergers; see, e.g., Burke-Spolaor et al. (2019). We will therefore keep an open mind and follow the latest literature.

3 Significance and scientific novelty

The length scales of magnetic fields produced at the electroweak phase transition would be extremely small. Turbulence, however, changes this picture because of the possibility of an inverse cascade (Brandenburg et al., 1996). In recent years, this topic has gained tremendous attention. This is connected with the observational impact both for the contemporary universe to interpret the lower magnetic field limits, and the early universe, where relic gravitational waves could be an important messenger. With our simulations, we will prepare the ground for probing physics of the first microseconds of the Universe, when important processes occurred, e.g., the development of the matter–antimatter asymmetry.

Over the last two decades, it has become clear that in astrophysics, the concept of Kolmogorov turbulence must be superseded by one involving magnetic fields. This is because in all astrophysical plasmas, magnetic fields strongly interact with turbulent flows. This leads to dynamo action, which is now understood to be unavoidable, i.e., dynamos always operate under turbulent conditions, which are ubiquitous. The significance of the Hosking integral is that it governs the evolution in many of these generic cases were magnetic helicity vanishes on average, but still plays a role locally. This concept is much broader than originally imagined: it also applies to neutrons star crusts (Brandenburg, 2020), to relativistic plasmas with fermion chirality canceling magnetic helicity (Brandenburg et al., 2023a), and to the decay of MHD turbulence with arbitrary initial spectra (Brandenburg et al., 2023b). There may be many more.

We envisage that the next decade will see a shift from simulations where the microphysics is captured entirely by numerical schemes to simulations with more realistic prescriptions of the microphysics. Standard Spitzer resistivity only applies to collisional plasmas. In collisionless plasmas, dissipation is governed by instabilities, which affect the cascade in nonlocal ways that might need to be incorporated. Recent work by Meyrand et al. (2019) shows that this can still be done in a fluid description.

We also envisage an increasing role played by magnetic helicity, both globally on average, and also locally within magnetic patches. We simulate this with the PENCIL CODE (Pencil Code Collaboration, 2021). However, many other codes do not use the magnetic vector potential. This has hampered the understanding of magnetic helicity in astrophysical plasmas, such as in the Sun, galaxies, and accretion discs.

4 Preliminary and previous results

The idea that C_{M} versus Lu saturates near $\mathrm{Lu}_{\mathrm{c}} = 2.5 \times 10^4$ is solely motivated by 2–D simulations and the proximity between the 2–D and 3–D results. This may not be very safe in view of the fact that there are systematic differences is between the two. While we see inverse cascading in both cases, the envelopes of the spectral magnetic peaks are different: $\propto k^{3/2}$ in 3–D, and $\propto k$ in 2–D. This has to do with the different conservation laws: the Hosking integral 3–D and the anastrophy (i.e., $\langle A_z^2 \rangle$) in 2–D; see Brandenburg et al. (2024) for details. Thus, while our results are interesting, they may still not provide a useful answer.

In MHD, one sometimes talks about 2.5 dimensional magnetic fields. Those are still two-dimensional in the sense that $\boldsymbol{B} = \boldsymbol{B}(x, y)$, but all three components may be finite. By contrast, in 2–D (in the restricted sense) one means a field $\boldsymbol{B}_\perp = \boldsymbol{\nabla} \times (\hat{\boldsymbol{z}} A_z) = (\partial_y A_z, -\partial_x A_z, 0)$. Such fields have zero magnetic helicity pointwise, so also the Hosking integral vanishes, but in 2.5–D, the Hosking integral is finite, and then the anastrophy is no longer conserved. As a test, we envisage (and will check) that $\langle \boldsymbol{B}_\perp^2 \rangle$ decays like $t^{-10/9}$, while $\langle B_z^2 \rangle$ should decay like t^{-1}. Whether 2.5–D simulations provide useful intermediate step for understanding turbulence in early universe needs to be checked carefully.

So far, only the groups using the PENCIL CODE and SNOOPY have been calculating magnetic helicity evolution and fluxes in their simulations. Furthermore, most other codes only have implicit dissipation, so a value of Lu cannot be defined unambiguously. It is therefore important to compute the actual dissipation, especially that of small-scale magnetic helicity. In Brandenburg & Scannapieco (2020), we have shown that the eight-wave MHD solver in the `FLASH` code suffers from artifacts in the magnetic helicity evolution. We expect and are therefore exploring the potential artifacts that emerge in such codes.

5 Project description

5.1 Theory and method

To model the evolution of the magnetic field after its generation during the radiation-dominated era, we perform very high resolution simulations of decaying turbulence and determine the decay rate in terms of the Alfvén time over a range of Lundquist and magnetic Prandtl numbers. These numbers characterize the resistivity and viscosity. One of the difficulties is to assess artifacts resulting from making compromises by choosing the position of the peak of the spectrum neither too close to the smallest wavenumber of the computational domain nor too close to the largest one, in which case the inertial range of the turbulence would not be large enough. Additional compromises can be made by invoking hyperviscosity and hyperresistivity. These tools tend to shorten the dissipation range and prolong the inertial range, but they also modify the problem in ways that may not yet be fully understood. Therefore, we will perform systematic studies of the dependence on all the secondary input parameters (scale separation toward $k \ll k_0$ and $k \gg k_0$, as well as the order of the diffusion operator in cases with hyperdiffusion).

By calculating the magnetically induced effect on density, we can assess the role of clumping and whether this significantly changes the sound horizon and thereby the effect on the Hubble tension (Jedamzik et al., 2025a). Specifically, we plan to determine the contrast of density structures that are

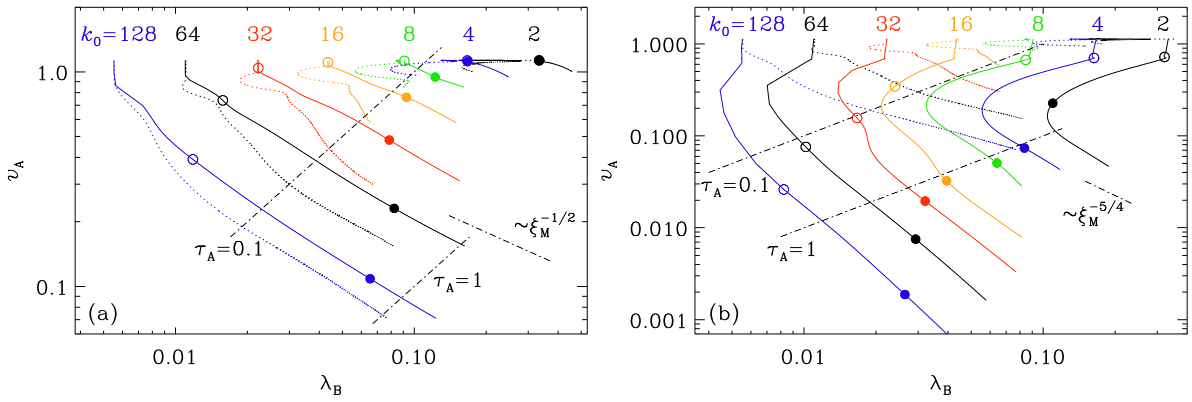

Figure 4: Parametric representation of $v_{\mathrm{A}} = B_{\mathrm{rms}}/\sqrt{\rho\mu_0}$ versus λ_B for helical (left) and nonhelical (right) initially columnar fields of different scale characterized by the fractional wavenumber $k_0 = 2$ (black), 4 (blue), 8 (green), and 16 (orange), 32 (red), 64 (black), and 128 (blue). The open (filled) symbols in both plots indicate the times $t = 10$ ($t = 100$). Adapted from Brandenburg et al. (2025).

caused by the magnetic field at the end of the radiation-dominated era. We also need to assess the damping caused by the photon fluid on the velocity field. This could shorten the decay time expressed in terms of the Alfvén time. These density fluctuations will also affect the resulting Biermann battery effect discussed in earlier work of Naoz & Narayan (2013) as alternative to earlier magnetogenesis scenarios.

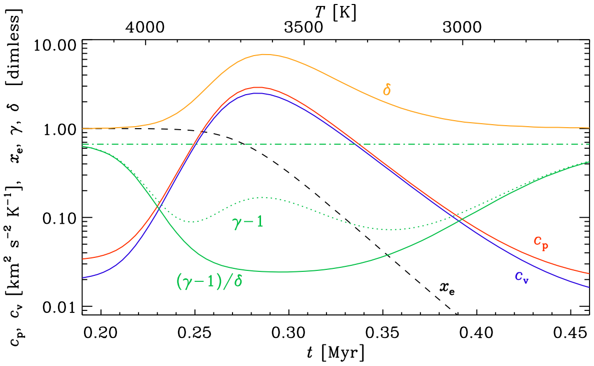

Figure 5: Dependences of c_{p} and c_{v}, as well as $\gamma = c_{\mathrm{p}}/c_{\mathrm{v}}$, the ionization fraction x_{e}, and $\alpha = (\partial \ln \rho / \partial \ln p)_T$, which enters in the expression for the sound speed $c_{\mathrm{s}} = \sqrt{\gamma p / \rho\alpha}$, where p is pressure.

Given that the correlation length $\lambda_B(t)$ and magnetic energy density $\mathcal{E}_{\mathrm{M}}(t)$ are power laws in time, it was thought that the values at time t,

$$\lambda_B(t) = \lambda_{B0}\left(\frac{t}{t_0}\right)^{\frac{4}{9}},\ \mathcal{E}_{\mathrm{M}}(t) = \mathcal{E}_{\mathrm{M0}}\left(\frac{t}{t_0}\right)^{-\frac{10}{9}} \tag{1}$$

depend on *two* adjustable parameters: $\lambda_{B0} \equiv \lambda_B(t_0)$ and $\mathcal{E}_{\mathrm{M0}} \equiv \mathcal{E}_{\mathrm{M}}(t_0)$, but we now know that the correct expression leaves less freedom (Brandenburg & Larsson, 2023; Brandenburg & Banerjee, 2025; Vachaspati, & Brandenburg, 2025)

$$\lambda_B(t) = C_{\mathrm{H}}^{\lambda} I_{\mathrm{H}}^{1/9} t^{4/9}, \quad \mathcal{E}_{\mathrm{M}}(t) = C_{\mathrm{H}}^{\mathcal{E}} I_{\mathrm{H}}^{2/9} t^{-10/9}, \tag{2}$$

and depends only on *one* parameter, the conserved quantity I_{H}, if it is indeed true that $C_{\mathrm{H}}^{\lambda} \approx 0.14$ and $C_{\mathrm{H}}^{\mathcal{E}} \approx 4.0$ are *universal* parameters. However, at least in the non-helical case, the evolution does not always start off as a straight power law; see Figure 4 where we compare helical (left) and non-helical cases (right) for two special initial conditions. Here the initial fields are columnar, which is motivated by what can be realized in a plasma experiment.

The theory of non-helical turbulent decay is not (yet) universally accepted, and some simulations yield different results (Armua et al., 2023; Dwivedi et al., 2024). Reasons include the occurrence of artifacts related to the to finite scale separation, or the use of hyperviscosity or time dependent, viscosity, or the slow-limited diffusion scheme used in some simulations. In the PENCIL CODE, we can test all these scenarios and compare with direct numerical simulations, where no such tools are employed.

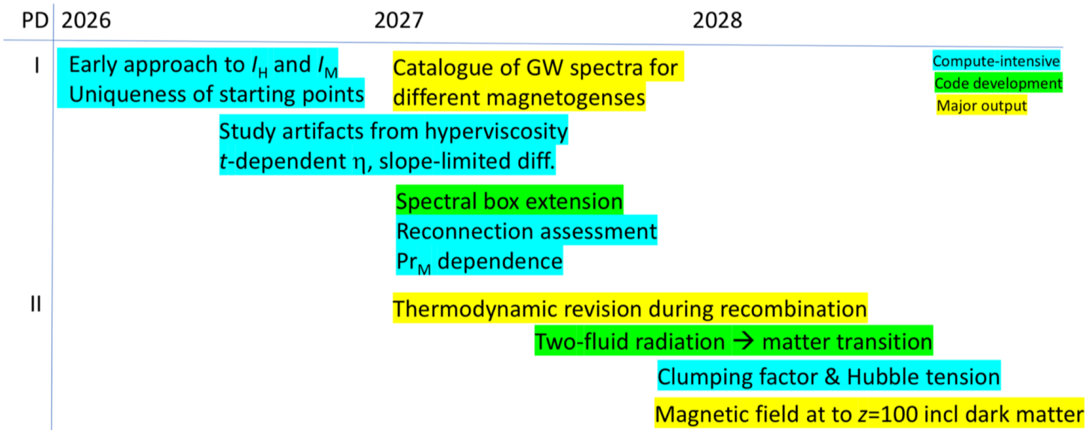

Figure 6: Time line of the project and tasks of PDs I and II. Compute-intensive and code development tasks are highlighted in blue and green, respectively, while major outputs are in yellow.

5.2 Time plan and implementation

We begin by assessing the artifacts resulting from the use of hyperviscosity and hyper-resistivity, the finite domain size, and dependence on the aspect ratio of the computational domain. These calculations will help us assessing the quality of a new technique to a propagate inversely cascading turbulence to larger domains as time goes on. Here we will employ a technique called spectral box extension, which can be performed in two ways: (i) by simply re-initializing a simulation from previously computed energy spectra by randomizing the phases in Fourier space, or (ii) by supplying random modes at the smallest wavenumbers only. This technique will need to be implemented into the PENCIL CODE and requires some code development. At the end of our exploration of different magnetogenesis scenarios, we will have a catalogue of new models of magnetic fields and their associated gravitational wave data that constitute a major output of our project. All this will be done by the first postdoc (PD I); see the timeline in Figure 6.

The second postdoc (PD II) will focus on all aspects related to understanding the magnetic field evolution at the transition from radiation to matter domination. I have started doing some exploratory calculations with the PENCIL CODE using the hydrogen ionization module. During recombination, many thermodynamic functions such as the specific heats at constant pressure and volume (c_p and c_v) and factors related to latent heat effects very significantly; see Figure 5. Such variations have been neglected in the work of Jedamzik et al. (2025a), so one of our major outputs will be the establishment of such thermodynamic variations and their effect on baryon clumping.

To model the transition to matter domination, Jedamzik et al. (2025a) initiated the simulations in a completely matter-dominated gas. While we may also do this with the PENCIL CODE, we plan to exploit a two-fluid framework in which the photon gas that was simulated in radiation domination is also included and coupled to the matter fluid. This also requires some code development.

Both with single and two-fluid models, we will compute the clumping factor that governs the reduction of the sound horizon at the time of recombination, which thereby contributes to alleviating the Hubble tension. This will be another compute-intensive step. As a major deliverable, our work will then produce magnetic field snapshots that also include the early dark matter evolution, which can be then be used in realistic ΛCDM models of the low red shift Universe; see, e.g., joint work with Mtchedlidze (2024).

Mile stones. We monitor the progress through the achievement of the following mile stones.

- Conclusive assessment regarding the artifacts and advantages of using hyperviscosity and hyperresistivity, the finite domain size effects, as well as dependence on the aspect ratio of the computational domain (during 2026).
- Catalogue of magnetic field and gravitational wave data from a range of magnetogenesis models (during 2027).
- New models with the spectral box extension (during 2027).
- Conclusive assessment regarding the magnetically produced baryon clumping and the effect of variations of thermodynamic properties during recombination (during 2028).
- Snapshots of magnetic field, density, and velocity at $z = 100$ with proper early dark matter evolution (during 2028).

Risks. Spectral box extension has so far only been used by simply re-initializing a simulation from previously computed energy spectra by randomizing the phases in Fourier space. If the technique of supplying random modes at the smallest wavenumbers only turns out to be problematic, the initializing from spectra is a fall-back option. It is also not clear whether the two-fluid framework with photon gas coupled to the matter fluid is needed. A fall-back option is to model only the transition to matter domination, as done by Jedamzik et al. (2025a). Another risk is to lose local in-house expertise in high-performance computing. This increases the demand on us for hands-on help in computing. Already now, we mitigate this by monthly PENCIL CODE office hours and disseminating information through the PENCIL CODE newsletter.

Backup plan. In addition to the risk mitigations addressed above, there are several alternative routes if the need emerges.

- The study of artifacts may not be conclusive. We should then attempt to provide tighter error margins on the scaling coefficients.
- Radiation may limit the time step prohibitively. We can then artificially lower the radiation field and study the scaling of the final results with this reduction.
- Alternative explanations for Hubble tension, intergalactic magnetic fields, or the stochastic gravitational wave background may gain increased attention. This would open many possibilities for backup studies if any other aspects of our project become problematic.

5.3 Project organization

At Nordita, most of my time is devoted to research. I am therefore able to spend at least 50% of my time on this project, which includes the supervision of two postdocs to be supported on this project. A committee will be set up to select the postdocs with the best competences (physical insight, numerical proficiency, etc). For the first postdoc, experience with turbulence will be beneficial, while for the second, experience with ΛCDM cosmology will be advantageous.

6 Equipment & Need for research infrastructure

This project utilizes national supercomputing resources through the National Academic Infrastructure for Supercomputing in Sweden (NAISS), which also provides resources on GPU cluster LUMI in Finland. National supercomputing resources have been used routinely by the PI. We are currently using 1.5 million

CPU hours per month at PDC in Stockholm and a smaller amount at NSC in Linköping. We also hold an allocation of 2.6 million CPU hours and 248 000 GPU hours on LUMI. This is usually sufficient to cover our regular needs for most of our production runs. In the event of very large computing needs, we plan to apply for European PRACE resources.

7 International and national collaboration

I enjoy a large network of international collaborators. Particularly important for this project is my collaboration with Chiara Caprini (Geneva), Andrii Neronov (Paris & Lausanne), and Franco Vazza (Bologna), as well as with Tina Kahniashvili (Carnegie Mellon U), Evangelos Sfakianakis (Case Western Reserve U), and Oksana Iarygina (Marie-Curie fellow at Nordita). There is also the community of PENCIL CODE users, and we meet annually during in-person PENCIL CODE User Meetings and monthly during office hours via zoom. During conferences in general, new collaborations have emerged spontaneously, as evidenced by the list of publications of the PI with new collaborations in recent years.

8 Independent line of research

As is evident from my CV, I have been managing small research groups during my entire career.

References

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Description of merits

Describe how the merits you state in the application confirm your competence as project leader and scientifically responsible for implementing the proposed activities, according to the instructions in the call text.

Description of merits (English)

Publications and other research outputs

Applicant's publications and other research outputs (English)

See following page for attachment

Publications

Axel Brandenburg (590407-8317)

1. Bibliometric information

Total number of peer-reviewed original articles: 464
Total number of citations of the peer-reviewed original articles: 29,202
H index (overall, not limited to the last 8 years): 85
i10 index (overall, not limited to the last 8 years): 406
Database used for above citation data: `https://scholar.google.se`

2. Selection of publications

The publication numbers refer to `https://axelbrandenburg.github.io/pub/node1.html`.

412. Pencil Code Collaboration: **Brandenburg, A.**, Johansen, A., Bourdin, P. A., +34 coauthors: 2021, "The Pencil Code, a modular MPI code for partial differential equations and particles: multipurpose and multiuser-maintained," *J. Open Source Softw.* **6**, 2807
The PI wrote the paper and the data that were reviewed by the referees. This paper reflects the synergetic effort of the PI for making this product available to the community.

410. Roper Pol, A., Mandal, S., **Brandenburg, A.**, Kahniashvili, T., & Kosowsky, A.: 2020, "Numerical Simulations of Gravitational Waves from Early-Universe Turbulence," *Phys. Rev. D* **102**, 083512
The PI wrote the code with the students, ran most of the simulations, and started the paper.

359. **Brandenburg, A.**, Kahniashvili, T., Mandal, S., Roper Pol, A., Tevzadze, A. G., & Vachaspati, T.: 2017, "Evolution of hydromagnetic turbulence from the electroweak phase transition," *Phys. Rev. D* **96**, 123528
The PI designed the numerical experiments, developed an alternative dimensional analysis highlighting the importance of the Planck mass in achieving helical magnetic fields beyond that produced by the chiral magnetic effect. The results imply the necessity of helicity during the electroweak epoch and thus the presence of circularly polarized gravitational waves.

350. **Brandenburg, A.**, Mathur, S., & Metcalfe, T. S.: 2017, "Evolution of coexisting long and short period stellar activity cycles," *Astrophys. J.* **845**, 79
This paper shows that most stars younger than 3 billion years have two cycles, whose periods are separated by a factor of about six. The PI carried out the investigation and wrote most of the paper.

344. **Brandenburg, A.**, & Kahniashvili, T.: 2017, "Classes of hydrodynamic and magnetohydrodynamic turbulent decay," *Phys. Rev. Lett.* **118**, 055102
The PI designed a new technique (the pq diagram) to diagnose different classes of self-similar turbulent decay. These new sets of simulations form the basis for our different sets of gravitational wave experiments produced in this project. They allow us to put hydrodynamic and hydromagnetic forcings used in this project on comparable footings.

340. **Brandenburg, A.**: 2016, "Stellar mixing length theory with entropy rain," *Astrophys. J.* **832**, 6
This paper establishes the idea of subadiabatic convection and provides an explanation for

the enthalpy flux in situations where it cannot be explained as a flux down the negative gradient.

322. **Brandenburg, A.**, Kahniashvili, T., & Tevzadze, A. G.: 2015, "Nonhelical inverse transfer of a decaying turbulent magnetic field," *Phys. Rev. Lett.* **114**, 075001
The PI developed the hypothesis that non-helical decaying hydromagnetic turbulence has a similar spectral energy transfer than helical turbulence. The proposed k^{-2} *scaling with wavenumber* k *can be tested by measuring the gravitational wave background. The extended hydrodynamic tail at small* k *is important for the gravitational wave spectrum.*

153. **Brandenburg, A.**, & Subramanian, K.: 2005, "Astrophysical magnetic fields and nonlinear dynamo theory," *Phys. Rep.* **417**, 1–209
The author develops the idea that magnetic helicity fluxes alleviate resistively limited inverse magnetic energy transfer. This work develops and employs the two-scale analysis as a new diagnostic techniques to be used in the present work to distinguish a hemispherically dependent EB *cross polarization from a global one.*

98. **Brandenburg, A.**: 2001, "The inverse cascade and nonlinear alpha-effect in simulations of isotropic helical hydromagnetic turbulence," *Astrophys. J.* **550**, 824–840
The author uses simulations and analytic models to develop a comprehensive theory for the evolution of magnetic fields in the presence of helical turbulent driving. This type of simulations forms the basis for part of the simulations used in the present work. The author used a precursor of the PENCIL CODE*, to be used in this project.*

54. **Brandenburg, A.**, Enqvist, K., & Olesen, P.: 1996, "Large-scale magnetic fields from hydromagnetic turbulence in the very early universe," *Phys. Rev. D* **54**, 1291–1300
The author developed the idea that helical hydromagnetic turbulence leads to magnetic length scales that are much larger than what was thought at the time, namely the comoving horizon scale at the time of magnetic field generation. This work provides the basic reference for the scaled equations used in this project.

3. Relevant publications from the last 8 years (2017–2025)

a. Peer-reviewed original articles (those of Sect. 2 are here omitted)

461. Vachaspati, T., & **Brandenburg, A.**: 2025, "Spectra of magnetic fields from electroweak symmetry breaking," *Phys. Rev. D* **111**, 043541

459. **Brandenburg, A.**, & Banerjee, A.: 2025, "Turbulent magnetic decay controlled by two conserved quantities," *J. Plasma Phys.* **91**, E5

458. **Brandenburg, A.**, Iarygina, O., Sfakianakis, E. I., & Sharma, R.: 2024, "Magnetogenesis from axion-SU(2) inflation," *J. Cosmol. Astropart. Phys.* **12**, 057

455. **Brandenburg, A.**, Neronov, A., & Vazza, F.: 2024, "Resistively controlled primordial magnetic turbulence decay," *Astron. Astrophys.* **687**, A186

454. Iarygina, O., Sfakianakis, E. I., Sharma, R.. & **Brandenburg, A.**: 2024, "Backreaction of axion-SU(2) dynamics during inflation," *J. Cosmol. Astropart. Phys.* **04**, 018

453. **Brandenburg, A.**, Clarke, E., Kahniashvili, T., Long, A. J., & Sun, G.: 2024, "Relic gravitational waves from the chiral plasma instability in the standard cosmological model," *Phys. Rev. D* **109**, 043534

452. Schober, J., Rogachevskii, I., & **Brandenburg, A.**: 2024, "Chiral anomaly and dynamos from inhomogeneous chemical potential fluctuations," *Phys. Rev. Lett.* **132**, 065101

450. **Brandenburg, A.**, Sharma, R., & Vachaspati, T.: 2023, "Inverse cascading for initial MHD turbulence spectra between Saffman and Batchelor," *J. Plasma Phys.* **89**, 905890606

448. **Brandenburg, A.**, Kamada, K., Mukaida, K., Schmitz, K., & Schober, J.: 2023, "Chiral magnetohydrodynamics with zero total chirality," *Phys. Rev. D* **108**, 063529

446. **Brandenburg, A.**, & Protiti, N. N.: 2023, "Electromagnetic conversion into kinetic and thermal energies," *Entropy* **25**, 1270

441. **Brandenburg, A.**, & Larsson, G.: 2023, "Turbulence with magnetic helicity that is absent on average," *Atmosphere* **14**, 932

440. **Brandenburg, A.**, Kamada, K., & Schober, J.: 2023, "Decay law of magnetic turbulence with helicity balanced by chiral fermions," *Phys. Rev. Res.* **5**, L022028

439. **Brandenburg, A.**: 2023, "Hosking integral in nonhelical Hall cascade," *J. Plasma Phys.* **89**, 175890101

436. **Brandenburg, A.**, Rogachevskii, I., & Schober, J.: 2023, "Dissipative magnetic structures and scales in small-scale dynamos," *Mon. Not. Roy. Astron. Soc.* **518**, 6367–6375

435. **Brandenburg, A.**, Zhou, H., & Sharma, R.: 2023, "Batchelor, Saffman, and Kazantsev spectra in galactic small-scale dynamos," *Mon. Not. Roy. Astron. Soc.* **518**, 3312–3325

433. Zhou, H., Sharma, R., & **Brandenburg, A.**: 2022, "Scaling of the Hosking integral in decaying magnetically-dominated turbulence," *J. Plasma Phys.* **88**, 905880602

428. **Brandenburg, A.**, & Ntormousi, E.: 2022, "Dynamo effect in unstirred self-gravitating turbulence," *Mon. Not. Roy. Astron. Soc.* **513**, 2136–2151

423. Haugen, N. E. L., **Brandenburg, A.**, Sandin, C., & Mattsson, L.: 2022, "Spectral characterisation of inertial particle clustering in turbulence," *J. Fluid Mech.* **934**, A37

422. **Brandenburg, A.**, He, Y., & Sharma, R.: 2021, "Simulations of helical inflationary magnetogenesis and gravitational waves," *Astrophys. J.* **922**, 192

421. **Brandenburg, A.**, & Sharma, R.: 2021, "Simulating relic gravitational waves from inflationary magnetogenesis," *Astrophys. J.* **920**, 26

419. **Brandenburg, A.**, Clarke, E., He, Y., & Kahniashvili, T.: 2021, "Can we observe the QCD phase transition-generated gravitational waves through pulsar timing arrays?" *Phys. Rev. D* **104**, 043513

417. **Brandenburg, A.**, Gogoberidze, G., Kahniashvili, T., Mandal, S., & Roper Pol, A., & Shenoy, N.: 2021, "The scalar, vector, and tensor modes in gravitational wave turbulence simulations," *Class. Quantum Grav.* **38**, 145002

408. **Brandenburg, A.**: 2020, "Hall cascade with fractional magnetic helicity in neutron star crusts," *Astrophys. J.* **901**, 18

405. **Brandenburg, A.**, Durrer, R., Huang, Y., Kahniashvili, T., Mandal, S., & Mukohyama S.: 2020, "Primordial magnetic helicity evolution with a homogeneous magnetic field from inflation," *Phys. Rev. D* **102**, 02353

404. **Brandenburg, A.**, & Furuya, R. S.: 2020, "Application of a helicity proxy to edge-on galaxies," *Mon. Not. Roy. Astron. Soc.* **496**, 4749–4759

402. **Brandenburg, A.**, & Brüggen, M.: 2020, "Hemispheric handedness in the Galactic synchrotron polarization foreground," *Astrophys. J. Lett.* **896**, L14

400. **Brandenburg, A.**, & Boldyrev, S.: 2020, "The turbulent stress spectrum in the inertial and subinertial ranges," *Astrophys. J.* **892**, 80

399. **Brandenburg, A.**, & Chen, L.: 2020, "The nature of mean-field generation in three classes of optimal dynamos," *J. Plasma Phys.* **86**, 905860110

398. **Brandenburg, A.**, & Scannapieco, E.: 2020, "Magnetic helicity dissipation and production in an ideal MHD code," *Astrophys. J.* **889**, 55

395. **Brandenburg, A.**, & Das, U.: 2020, "The time step constraint in radiation hydrodynamics," *Geophys. Astrophys. Fluid Dyn.* **114**, 162–195

390. **Brandenburg, A.**: 2019, "A global two-scale helicity proxy from π-ambiguous solar magnetic fields," *Astrophys. J.* **883**, 119

387. **Brandenburg, A.**, & Rempel, M.: 2019, "Reversed dynamo at small scales and large magnetic Prandtl number," *Astrophys. J.* **879**, 57

386. **Brandenburg, A.**: 2019, "Ambipolar diffusion in large Prandtl number turbulence," *Mon. Not. Roy. Astron. Soc.* **487**, 2673–2684

383. **Brandenburg, A.**, Kahniashvili, T., Mandal, S., Roper Pol, A., Tevzadze, A. G., & Vachaspati, T.: 2019, "Dynamo effect in decaying helical turbulence," *Phys. Rev. Fluids* **4**, 024608

380. **Brandenburg, A.**, Bracco, A., Kahniashvili, T., Mandal, S., Roper Pol, A., Petrie, G. J. D., & Singh, N. K.: 2019, "E and B polarizations from inhomogeneous and solar surface turbulence," *Astrophys. J.* **870**, 87

378. **Brandenburg, A.**: 2018, "Magnetic helicity and fluxes in an inhomogeneous α^2 dynamo," *Astron. Nachr.* **339**, 631–640

377. **Brandenburg, A.**, & Oughton, S.: 2018, "Cross-helically forced and decaying hydromagnetic turbulence," *Astron. Nachr.* **339**, 641–646

371. **Brandenburg, A.**: 2018, "Advances in mean-field dynamo theory and applications to astrophysical turbulence," *J. Plasma Phys.* **84**, 735840404

369. **Brandenburg, A.**, Durrer, R., Kahniashvili, T., Mandal, S., & Yin, W. W.: 2018, "Statistical properties of scale-invariant helical magnetic fields and applications to cosmology," *J. Cosmol. Astropart. Phys.* **08**, 034

367. **Brandenburg, A.**, Haugen, N. E. L., Li, X.-Y., & Subramanian, K.: 2018, "Varying the forcing scale in low Prandtl number dynamos," *Mon. Not. Roy. Astron. Soc.* **479**, 2827–2833

362. **Brandenburg, A.**, & Giampapa, M. S.: 2018, "Enhanced stellar activity for slow antisolar differential rotation?" *Astrophys. J. Lett.* **855**, L22

346. **Brandenburg, A.**: 2017, "Analytic solution of an oscillatory migratory α^2 stellar dynamo," *Astron. Astrophys.* **598**, A117

b. Peer-reviewed conference contributions (results not included elsewhere)

C.86. Kahniashvili, T., **Brandenburg, A.**, Kosowsky, A., Mandal, S., & Roper Pol, A.: 2020, "Magnetism in the early universe," in *Astronomy in Focus, Vol. 14*, ed. M. T. Lago, ed., Proc. IAU Symp. A30, pp. 295–298

d. Research review articles

443. **Brandenburg, A.**, & Ntormousi, E.: 2023, "Galactic Dynamos," *Annu. Rev. Astron. Astrophys.* **61**, 561–606

B.40. **Brandenburg, A.**: 2020, "Magnetic field evolution in solar-type stars," in *IAUS 354: Solar and Stellar Magnetic Fields: Origins and Manifestations*, ed. A. Kosovichev, K. Strassmeier & M. Jardine, Proc. IAU Symp., Vol. **354**, pp. 169–180

e. Peer-reviewed books and book chapters

B.43. **Brandenburg, A.**, Larsson, G.: 2024, "Turbulence with magnetic helicity that is absent on average" in *Turbulence from Earth to Planets, Stars and Galaxies—Commemorative Issue Dedicated to the Memory of Jackson Rea Herring*, ed. B. Galperin, A. Pouquet, & P. Sullivan, MDPI Books, pp. 123–139

B.42. **Brandenburg, A.**: 2022, "Chirality in Astrophysics" in *Proceedings to Nobel Symposium 167: Chiral Matter*, ed. E. Babaev, D. Kharzeev, M. Larsson, A. Molochkov, & V. Zhaunerchyk, World Scientific, pp. 15–35

B.41. **Brandenburg, A.**: 2021, "Homochirality: a prerequisite or consequence of life?" in *Prebiotic Chemistry and the Origin of Life*, ed. A. Neubeck, & S. McMahon, Springer, pp. 87–115

f. Other publications including popular science books/presentations

E.39. **Brandenburg, A.**: 2014, "Sökandet efter en ny teori för solfläckar," *Fysikaktuellt* **2014-1**, 22–23, `http://www.fysikersamfundet.se/Fysikaktuellt/2014_1.pdf`

Participating researcher's publications and other research outputs (English)

No file has been uploaded

Budget and research resources

Project personnel

Activity level in the project

	Role in the project	Name	Percent of full time
1	Applicant	Axel Brandenburg	

Salaries including social fees

Role in the project	Name		Percent of salary
	2026	2027	2028
No information added			

Other costs

Premises

Type of premises	2026	2027	2028
No information added			

Running Costs

Running Cost	Description	2026	2027	2028
No information added				

Depreciation costs

Depreciation cost	Description	2026	2027	2028
No information added				

Total cost

Total Budget

	Specified costs	2026	2027	2028	Total, applied	Other costs	Total cost
1	Salaries including social fees				0		0
2	Running costs				0		0
3	Depreciation costs				0		0
4	Premises				0		0
5	Subtotal	0	0	0	0	0	0
6	Indirect costs				0		0
7	Total project cost	0	0	0	0	0	0

Justification of the budget applied for

Justification of the budget applied for (English)

Other funding

Other funding for this project

Funder	Applicant/project leader	Type of grant	Status	Reg no or equiv.
	2026	2027		2028
No information added				

CV

CV - Axel Brandenburg

Project leader: Axel Brandenburg	**Doctoral degree:** 1990-04-18
Birthdate: 19590407	**Academic title:** Professor
Gender: Male	**Employer:** Nordita
Country: Sweden	

Doctors degree

Examination	Organisation	Dissertation title (original language)	Supervisor
10305. Astronomy, Astrophysics and Cosmology, 1990-04-18	University of Helsinki, Department of Astronomy	Challenges for dynamo theory: alpha effect, differential rotation and stability	Ilkka Tuominen

Educational history

Research education

Examination	Organisation	Dissertation title	Name of supervisor
PhD degree, 10305. Astronomy, Astrophysics and Cosmology, 1990-04-18	University of Helsinki, Finland, Department of Astronomy	Challenges for dynamo theory: alpha effect, differential rotation and stability	Ilkka Tuominen

Basic education

Year	Examination
1986	10305. Astronomy, Astrophysics and Cosmology, Higher Education Diploma, University of Hamburg, Germany

Professional history

Employments

Period	Position	Part of research in employment	Employer	Other information
september 2018 - april 2028	Professor, Permanent employment	0	Stockholm University, Sweden, Department of Astronomy	

Period	Position	Part of research in employment	Employer	Other information
september 2018 - april 2028	Professor, Permanent employment	100	Stockholm University, Sweden, Nordic Institute for Theoretical Physics (NORDITA)	
september 2015 - augusti 2018	Professor, Permanent employment	0	Stockholm University, Sweden, Department of Astronomy	
september 2015 - augusti 2018	Professor, Permanent employment	25	Nordita	
augusti 2015 - maj 2018	Professor, Temporary position	75	University of Colorado, United States, Department of Astrophysical & Planetary Sciences	Visiting faculty position
januari 2007 - augusti 2015	Professor, Permanent employment	100	Nordita	
januari 2000 - december 2006 (Present)	Professor, Permanent employment	100	Nordita	
februari 1996 - januari 2000	Professor, Permanent employment	100	Newcastle University, United Kingdom, Applied Mathematics	
december 1994 - januari 1996	Assistant professor, Temporary position	100	Nordita	

Post doctoral assignments

Period	Organisation	Subject
december 1992 - november 1994	NCAR (Boulder), United States, High Altitude Observatory	10305. Astronomy, Astrophysics and Cosmology
augusti 1992 - november 1992	University of Cambridge, United Kingdom, DAMTP	10305. Astronomy, Astrophysics and Cosmology
september 1990 - juli 1992	Nordita, Denmark	10305. Astronomy, Astrophysics and Cosmology

Merits and awards

Docentur

Year	Subject	Organisation
1992	10305. Astronomy, Astrophysics and Cosmology	University of Helsinki, Finland, Astronomy

Supervised persons

Year	Supervised persons	University (supervisee)	Role
2024	PhD student, Yutong He	Stockholm University, Sweden	Main supervisor
2019	PhD student, Illa R. Losada	Stockholm University, Sweden, Institutionen för astronomi	Main supervisor
2016	PhD student, Sarah Jabbari	Stockholm University, Sweden	Main supervisor
2013	PhD student, Joern Warnecke	Stockholm University, Sweden	Main supervisor
2012	PhD student, Fabio Del Sordo	Stockholm University, Sweden	Main supervisor
2012	PhD student, Koen Kemel	Stockholm University, Sweden	Main supervisor
2012	PhD student, Simon Candelaresi	Stockholm University, Sweden	Main supervisor
2000	PhD student, Alberto Bigazzi	Newcastle University, United Kingdom	Main supervisor
2000	PhD student, Stephen J. Brooks	Newcastle University, United Kingdom	Main supervisor
1999	PhD student, Maarit Korpi	University of Oulu, Finland	Main supervisor
2018	PhD student, Xiang-Yu Li	Stockholm University, Sweden	Secondary supervisor
2004	PhD student, Nils E. L. Haugen	Norwegian University of Science and Technology, Norway	Secondary supervisor
2004	PhD student, Tarek Yousef	Norwegian University of Science and Technology, Norway	Secondary supervisor
2023	Postdoc, Ramkishor Sharma	Stockholm University, Sweden	Main supervisor
2017	Postdoc, Nishant Singh	Stockholm University, Sweden, Nordita	Main supervisor

Research grants awarded in competition

Period	Funder	Project leader	Your role	Sub amount (SEK)	Total amount (SEK)
2020 - 2023	VR - The Swedish Research Council, Sweden - Other financing agencies and organisations	Axel Brandenburg	Applicant	0	4 000 000
2017 - 2019	Not Sweden - Higher education institutes,	Axel Brandenburg	Applicant	0	2 000 000
2015 - 2019	Sweden - Oterh private actors,	Bernhard Mehlig	Co-applicant	7 000 000	44 000 000
2014 - 2017	Not Sweden - Higher education institutes,	Axel Brandenburg	Applicant	0	7 250 000
2013 - 2016	VR - The Swedish Research Council, Sweden - Other financing agencies and organisations	Axel Brandenburg	Applicant	0	4 200 000
2012 - 2014	Sweden - Higher education institutions,	Axel Brandenburg	Applicant	0	1 650 000
2009 - 2014	European Union (EU),	Axel Brandenburg	Applicant	0	22 200 000
1998 - 2001	Not Sweden - Higher education institutes,	Axel Brandenburg	Applicant	0	3 700 000

Other merits

Period	Type of merit	Description
2010 - 2026	Editorial Board Member	Editorial Board Member of Astronomische Nachrichten
2018 - 2024	Adjunct Professorship	Adjunct Professor at the Department of Physics at Carnegie Mellon University
2019 - 2020	Guest editor	Guest editor of Geophysical and Astrophysics Fluid Dynamics.
2013 - 2013	Invited plenary speaker at major conference	European Turbulence Conference, ETC14, 55 min, 500-600 participants, http://etc14.ens-lyon.fr/registration/
2012 - 2012	Organized major conference	12th European Workshop on Astrobiology (EANA 2012), https://agenda.albanova.se/conferenceDisplay.py?confId=2996
2011 - 2012	Guest editor	Guest editor of Geophysical and Astrophysics Fluid Dynamics.
2014	Academy member	Elected foreign member of the Royal Swedish Academy's class for astronomy and spacescience

Intellectual property

Intellectual property Type	Date of approval	Status	ID	Licensed to other part	Product classification
Personally developed public available software	2018-12-16	Approved	DOI:10.5281/zenodo.2315093	No	96. Other personal services

Register

Terms and conditions

The application shall be signed by the applicant and also by an authorised representative of the administrating organisation. The representative is normally the head of the department where the research will be carried out, but this is dependent on the administrating organisation’s structure.

The *applicant’s* signature confirms that

- the information in the application is correct and complies with the Swedish Research Council’s instructions
- secondary occupations and commercial ties have been reported to the administrating organisation and that nothing has emerged that breaches good research practice
- the permits and approvals required have been obtained before the research is started, such as permits from the Swedish Medical Products Agency or approval from The Swedish Ethical Review Authority or an ethical committee on animal experiments
- the applicant will comply with all other conditions applicable to the grant.

The signature of the *administrating organisation* confirms that

- the research or research-supporting activities described can be given room at the administrating organisation during the period and to the extent stated in the application
- the applicant will be employed by the administrating organisation during the period covered by the application
- the administrating organisation approves of the budget in the application
- the administrating organisation will comply with all other conditions applicable to the grant.

The above points shall have been discussed by the parties before the representative of the administrating organisation approves and signs the application.