2025-03-27

Scientific report

Information about the grant

Registration number: 2019-04234

Grant recipient: Brandenburg, Axel

Administrating organisation: Stockholms universitet

Project site: Nordic Institute for Theoretical Physics (NORDITA)

Project title (English): Stochastic Gravitational Wave Background from the Early Turbulent Universe

Grant period: 2020-01-01 - 2023-12-31

Total granted amount: 4,000,000

Availability period (end date): 2024-12-31

Call name: Research Grants Open call 2019 (Natural and Engineering Sciences)

Type of grant: Research Project Grant

Focus: Undirected

Area of science: NE

Information about the report

Type: Scientific - Single occurence

Period report refers to: 2020-01-01 - 2024-12-31

Scientific report registered and submitted by:

Project information

Project participant information

List the project participant(s) that were important to the project's implementation.

Project participant information

Project participant information

Project participator 1

Last name*	**First name ***
Brandenburg	Axel
Gender *	**Year Of birth***
Male	1959-04-07
Year of doctoral degree	**Role in the project***
1990	Applicant
Area of expertise*	**Dissertation within the project**
1. Natural Sciences > 103. Physical Sciences > 10305. Astronomy, Astrophysics and Cosmology	Yes
Organisation*	**Employment category***
Nordita	Professor

Project participant information

Project participator 2

Last name*	**First name ***
Kahniashvili	Tinatin
Gender *	**Year Of birth***
Female	1962-10-27
Year of doctoral degree	**Role in the project***
1988	Participating researcher
Area of expertise*	**Dissertation within the project**
1. Natural Sciences > 103. Physical Sciences > 10305. Astronomy, Astrophysics and Cosmology	Yes
Organisation*	**Employment category***
Carnegie Mellon University	Professor

Classifications

Choose a minimum of one and a maximum of three SCB-codes matching your project, by order of priority.

SCB-codes

10305. Astronomy, Astrophysics and Cosmology

Keywords

Enter a minimum of three and a maximum of five keywords describing the project.

Keyword 1

gravitational waves

Keyword 2

early universe

Keyword 3

magnetohydrodynamics

Keyword 4

turbulence

Keyword 5

magnetic helicity

Sustainable Development Goals (Agenda 2030)

Indicate whether the research results within your project are relevant to the Sustainable Development Goals (Agenda 2030). A maximum of three goals can be specified.

Sustainable Development Goals

99. No sustainable development goal / Not applicable

16. Peace, justice and strong institutions

Use of research infrastructure

Indicate any research infrastructures that have enabled research within the project.

Use of research infrastructure

Use of research infrastructure

Research infrastructure 1

Name of research infrastructure*	The importance of infrastructure for conducting the research*
SNIC (Swedish National Infrastructure for Computing)	Crucial

Project results

Description of project results

Describe the research question/s that has been addressed by the project.

Since 2017, we have developed a gravitational wave (GW) module for the Pencil Code to solve for GWs emanating from early Universe turbulence and magnetic fields. Our recent work had already demonstrated, using high-resolution 3-D turbulence simulations that GWs at observable levels can be produced. Several important new questions have then emerged that formed the focus of the present proposal. Specifically, we asked what is the efficiency of GW production through acoustic turbulence. What is the difference between GW production from forced and decaying turbulence? How does GW production depend on the energy-carrying length scale of the turbulence? What are the effects of magnetically and kinetically dominated turbulence on the GWs? How does the GW production depend on the duration of phase-transition-produced turbulence? Finally, how does GW production depend on the turbulent intensity and thus the Mach number?

There were several related questions that we also worked on through collaborations at Nordita. These include the question, can we obtain additional and independent evidence for early Universe-produced magnetic fields through the measurement of the arrival directions of energetic particles with Fermi LAT. Next, can we detect evidence for helicity of a primordial magnetic field in the cosmic microwave radiation background. And finally, how safe is the assumption that the non-detection of GeV cascade photons from the halos of blazars is caused by magnetic fields.

Briefly describe the most important research results achieved by the project.

We have performed numerical simulations of gravitational waves (GWs) induced by hydrodynamic and hydromagnetic turbulent sources that might have been present at cosmological phase transitions and/or during inflation. At the beginning of the project, we expected that the detailed time dependence of the source it crucial. We have considered GWs generated from the chiral magnetic effect on the one hand and from inflation on the other. The speed of generation and the speed characterizing the maximum magnetic field strength turn out to be crucial. When the generation speed exceeds a certain value, the GW energy continues to increase without a corresponding increase of magnetic energy.

At and below the peak frequency, the stress spectrum is always found to be that of white noise. This implies a linear increase of GW energy per logarithmic wavenumber interval, instead of a cubic one, as previously thought. Both in the helical and nonhelical cases, the GW spectrum is followed by a sharp drop for frequencies above the respective peak frequency. This is an important new result whose deeper origin is still not well understood. The fractional circular polarization is found to be nearly hundred per cent in a certain range below the peak frequency range.

In the middle of the project, a completely unexpected results emerged that allows us to predict the detailed evolution of non-helical magnetic fields and that provides an understanding of our earlier results. We have verified these results and extended them to other astrophysical bodies such as neutron stars and also to times prior to the electroweak phase transitions. Here, our work on the chiral magnetic effect also plays an important role in relevant situations where the magnetic field is fully helical, but this helicity is canceled by fermion chirality.

Another important finding concerns GW spectrum produced by acoustic waves in the early universe, such as would be produced by a first order phase transition. We have confirmed with numerical simulations the sound shell model prediction of a steep rise. We also show that hitherto neglected terms give a shallower part at low frequencies. For slow phase transitions, the acoustic GW peak appears as a localized enhancement of the spectrum, with a rise to the peak less steep. The shape of the peak, absent in vortical turbulence, may help to lift degeneracies in phase transition parameter estimation at future GW observatories.

Publications

- List the publications that **are a result of the project.**
- Only include articles or corresponding that have been published or accepted for publication.
- Enter your publications under the appropriate category.
- List the publications according to an accepted standard for your subject area.
- Write the author names in the same order as on the publication.
- Enter DOI, ISBN or other unique identifier.

Under the categories **Peer-reviewed original articles** and **Peer-reviewed conference contributions** you must only include articles published with open access. For **Peer-reviewed original articles** the registration number of the grant must be clearly stated under the heading "Acknowledgments" or the corresponding heading in the publication.

Peer-reviewed original articles

Vachaspati, T., & Brandenburg, A.: 2025, ``Spectra of magnetic fields from electroweak symmetry breaking,'' Phys. Rev. D 111, 043541, DOI: 10.1103/PhysRevD.111.043541

Brandenburg, A., & Banerjee, A.: 2025, ``Turbulent magnetic decay controlled by two conserved quantities,'' J. Plasma Phys. 91, E5, DOI: 10.1017/S0022377824001508

Brandenburg, A., Iarygina, O., Sfakianakis, E. I., & Sharma, R.: 2024, ``Magnetogenesis from axion-SU(2) inflation,'' J. Cosmol. Astropart. Phys. 12, 057, DOI: 10.1088/1475-7516/2024/12/057

Brandenburg, A., Neronov, A., & Vazza, F.: 2024, ``Resistively controlled primordial magnetic turbulence decay,'' Astron. Astrophys. 687, A186, DOI: 10.1051/0004-6361/202449267

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, DOI:

10.1103/PhysRevD.109.043534

Sharma, R., Dahl, J., Brandenburg, A., & Hindmarsh, M.: 2023, ``Shallow relic gravitational wave spectrum with acoustic peak,'' J. Cosmol. Astropart. Phys. 12, 042, DOI: 10.1088/1475-7516/2023/12/042

Brandenburg, A., Sharma, R., & Vachaspati, T.: 2023, ``Inverse cascading for initial MHD turbulence spectra between Saffman and Batchelor,'' J. Plasma Phys. 89, 905890606, DOI: 10.1017/S0022377823001253

Carenza, P., Sharma, R., Marsh, M. C. D., Brandenburg, A., Müller, E.: 2023, ``Magnetohydrodynamics predicts heavy-tailed distributions of axion-photon conversion,'' Phys. Rev. D 108, 103029, DOI: 10.1103/PhysRevD.108.103029

Brandenburg, A., Kamada, K., Mukaida, K., Schmitz, K., & Schober, J.: 2023, ``Chiral magnetohydrodynamics with zero total chirality,'' Phys. Rev. D 108, 063529, DOI: 10.1103/PhysRevD.108.063529

He, Y., Roper Pol, A., & Brandenburg, A.: 2023, ``Modified propagation of gravitational waves from the early radiation era,'' J. Cosmol. Astropart. Phys. 06, 025, DOI: 10.1088/1475-7516/2023/06/025

Brandenburg, A., Kamada, K., & Schober, J.: 2023, ``Decay law of magnetic turbulence with helicity balanced by chiral fermions,'' Phys. Rev. Res. 5, L022028, DOI: 10.1103/PhysRevResearch.5.L022028

Mtchedlidze, S., Domínguez-Fernández, P., Du, X., Schmidt, W., Brandenburg, A., Niemeyer, J., & Kahniashvili, T.: 2023, ``Inflationary and phase-transitional primordial magnetic fields in galaxy clusters,'' Astrophys. J. 944, 100, DOI: 10.3847/1538-4357/acb04d

Brandenburg, A., Rogachevskii, I., & Schober, J.: 2023, ``Dissipative magnetic structures and scales in small-scale dynamos,'' Mon. Not. Roy. Astron. Soc. 518, 6367-6375, DOI: 10.1093/mnras/stac3555

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, DOI: 10.1093/mnras/stac3217

Sharma, R., & Brandenburg, A.: 2022, ``Low frequency tail of gravitational wave spectra from hydromagnetic turbulence,'' Phys. Rev. D 106, 103536, DOI: 10.1103/PhysRevD.106.103536

Zhou, H., Sharma, R., & Brandenburg, A.: 2022, ``Scaling of the Hosking integral in decaying magnetically-dominated turbulence,'' J. Plasma Phys. 88, 905880602, DOI: 10.1017/S002237782200109X

Kahniashvili, T., Clarke, E., Stepp, J., & Brandenburg, A.: 2022, ``Big bang nucleosynthesis limits and relic gravitational wave detection prospects,'' Phys. Rev. Lett. 128, 221301, DOI: 10.1103/PhysRevLett.128.221301

Brandenburg, A., & Ntormousi, E.: 2022, ``Dynamo effect in unstirred self-gravitating turbulence,'' Mon. Not. Roy. Astron. Soc. 513, 2136-2151, DOI: 10.1093/mnras/stac982

Mtchedlidze, S., Domínguez-Fernández, P., Du, X., Brandenburg, A., Kahniashvili, T., O'Sullivan, S., Schmidt, W., & Brüggen, M.: 2022, ``Evolution of primordial magnetic fields during large-scale structure formation,'' Astrophys. J. 929, 127, DOI: 10.3847/1538-4357/ac5960

Roper Pol, A., Mandal, A., Brandenburg, A., & Kahniashvili, T.: 2022, ``Polarization of gravitational waves from helical MHD turbulent sources,'' J. Cosmol. Astropart. Phys. 04, 019, DOI: 10.1088/1475-7516/2022/04/019

Brandenburg, A., He, Y., & Sharma, R.: 2021, ``Simulations of helical inflationary magnetogenesis and gravitational waves,'' Astrophys. J. 922, 192, DOI: 10.3847/1538-4357/ac20d9

Brandenburg, A., & Sharma, R.: 2021, ``Simulating relic gravitational waves from inflationary magnetogenesis,'' Astrophys. J. 920, 26, DOI: 10.3847/1538-4357/ac1599

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, DOI:

10.1103/PhysRevD.104.043513

He, Y., Brandenburg, A., & Sinha, A.: 2021, ``Spectrum of turbulence-sourced gravitational waves as a constraint on graviton mass,'' J. Cosmol. Astropart. Phys. 07, 015, 10.1088/1475-7516/2021/07/015

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, DOI: 10.1088/1361-6382/ac011c

Brandenburg, A., He, Y., Kahniashvili, T., Rheinhardt, M., & Schober, J.: 2021, ``Gravitational waves from the chiral magnetic effect,'' Astrophys. J. 911, 110, DOI: 10.3847/1538-4357/abe4d7

Kahniashvili, T., Brandenburg, A., Gogoberidze, G., Mandal, S., & Roper Pol, A.: 2021, ``Circular polarization of gravitational waves from early-universe helical turbulence,'' Phys. Rev. Res. 3, 013193, DOI: 10.1103/PhysRevResearch.3.013193

Asplund, J., Johannesson, G., & Brandenburg, A.: 2020, ``On the measurement of handedness in Fermi Large Area Telescope data,'' Astrophys. J. 898, 124,
DOI: 10.3847/1538-4357/ab9744

Peer-reviewed conference contributions

Peer-reviewed edited volumes

Research review articles

Pencil Code Collaboration: Brandenburg, A., Johansen, A., Bourdin, P. A., Dobler, W., Lyra, W., Rheinhardt, M., Bingert, S., Haugen, N. E. L., Mee, A., Gent, F., Babkovskaia, N., Yang, C.-C., Heinemann, T., Dintrans, B., Mitra, D., Candelaresi, S., Warnecke, J., Käpylä, P. J., Schreiber, A., Chatterjee, P., Käpylä, M. J., Li, X.-Y., Krüger, J., Aarnes, J. R., Sarson, G. R., Oishi, J. S., Schober, J., Plasson, R., Sandin, C., Karchniwy, E., Rodrigues, L. F. S., Hubbard, A., Guerrero, G., Snodin, A., Losada, I. R., Pekkilä, J., & Qian, C.: 2021, ``The Pencil Code, a modular MPI code for partial differential equations and particles: multipurpose and multiuser-maintained,'' *J. Open Source Softw.* **6**, 2807

Peer-reviewed books and book chapters

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

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

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

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

Other publications including popular science books/presentations and working papers

Brandenburg, A.: 2020, *Scientific usage of the Pencil Code*. DOI:10.5281/zenodo.3466444

Categorisation of results

Categorise the project's most important research results by specifying the type and description for each result.

Categorisation of results

Categorisation of results
Categorisation 1

Type of result*

Artistic and Creative Products > Creative writing

Description*

Creative writing is the main output of my research. This is evidenced by the volume and impact of my original publications.

Source (e.g. website)

https://axelbrandenburg.github.io/pub/node1.html

Categorisation of results
Categorisation 2

Type of result*

Organisation and Management > Other

Description*

The Pencil Code is now managed through a steering committee with myself being part of it. Updates to the Pencil Code User Community are provided through regular newsletters.

Source (e.g. website)

https://github.com/pencil-code/website/tree/master/NewsLetters

Categorisation of results
Categorisation 3

Type of result*

Research Tools and Methods > Improvements to research infrastructure

Description*

I have provided continued improvements and additions to the Pencil Code in conjunction with an increasing community of other contributors. This is evidenced by the GitHub record of contributions.

Source (e.g. website)

https://github.com/pencil-code/pencil-code/graphs/contributors

Intellectual property

Indicate any intellectual property that result from the project.

Intellectual property

Company

List any companies that have emerged within / as a result of the research conducted.

Company

Popular scientific summary of results

Popular scientific summary of results, in Swedish

The following popular scientific description of the research results may be used for publication.

Please note that the text must be written in Swedish.

Describe in popular science terms the most important research results achieved by the project. If relevant, please also describe the social benefit and expected impacts on society resulting from the research results.

Den direkta upptäckten av gravitationsvågor har öppnat ett nytt fönster för observationsastronomi. Förutom händelser från diskreta källor som sammanslagningar av svarta hål och neutronstjärnor, bidrar turbulens i det mycket unga universum med ett betydande bidrag till en isotrop gravitationsvåg-bakgrund. Det finns nu allt mer bevis för en lågfrekvensbakgrund i nano-Hertz-området. Detta projekt gör kvantitativa förutsägelser för denna bakgrund genom numeriska simuleringar.

Betydelsen av denna gravitationsvåg-bakgrund är att den speglar förhållandena när universum var mindre än en mikrosekund gammalt. Det var under denna tid som viktiga, men fortfarande dåligt förstådda, fysiska processer inträffade, såsom materiens dominans över antimateria i universum. Det var också under denna epok som den svaga och elektromagnetiska kraften separerades och där kvarkar blev bundna till att bilda protoner, neutroner, etc. Gravitationsvåg-bakgrunden innehåller värdefull information om spektrumet av primordial turbulens och dess potentiellt icke-symmetriska egenskaper. På sätt och vis liknar det den berömda kosmiska bakgrundsstrålningen, som främst speglar universums förhållanden när det var 400 000 år gammalt.

Vårt arbete har gett de första fullt tredimensionella numeriska simuleringarna av gravitationsvågor från en numerisk realisering av turbulens på en dator. Detta gav oss nya insikter som tidigare inte hade förutsetts. Mest anmärkningsvärt är att vi fann att vid frekvenser under det dominerande toppvärdet är spektrumet flackare än vad man tidigare förväntat sig baserat på det som förväntas från slumpmässigt brus. Detta nya resultat är nu redan accepterat inom den vetenskapliga gemenskapen och har lett till viktiga revideringar av vår tidigare förståelse av gravitationsvåg-bakgrunden.

Under vårt projekt framkom en teoretisk förklaring av ett tidigare resultat som förklarar vår upptäckt att även statistiskt spegel-symmetrisk turbulens kan leda till en tillväxt av det turbulenta magnetiska fältet och hastighetsspektrumet vid stora längdskalor. Detta troddes tidigare bara vara möjligt för turbulens som bryter statistisk spegelsymmetri. Detta ledde till insikten att vi kan använda observationer av magnetfält i universums tommaste delar som ytterligare sonder av universum under de första mikrosekunderna av dess existens.