EXTRAGALACTIC MAGNETISM WITH SOFIA: FIRST RESULTS

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KIPAC/Stanford
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<thead>
<tr>
<th>Team Member</th>
<th>Affiliation</th>
</tr>
</thead>
<tbody>
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<td>Universite Paris Sud Institut d’Astrophysique Spatiale, France</td>
</tr>
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<td>Susan Clark</td>
<td>Stanford University, USA</td>
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<td>University of Wyoming, USA</td>
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<td>University of Crete, Greece</td>
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<td>Jet Propulsion Laboratory, USA</td>
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<tr>
<td>Lucas Grosset</td>
<td>KIPAC, Stanford University, USA</td>
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<td>Doyal A. Harper</td>
<td>University of Chicago, USA</td>
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<td>IRAP, Toulouse, France</td>
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<td>KICC, Cambridge, UK —&gt; KIPAC/Stanford, USA</td>
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<td>University of Crete, Greece</td>
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<tr>
<td>Alejandro Serrano Borlaff</td>
<td>NASA Ames, USA</td>
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<td>Kandaswamy Sugramanian</td>
<td>Inter-University Centre for Astronomy and Astrophysics, India</td>
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<td>Konstantinos Tassis</td>
<td>University of Crete, Greece</td>
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<td>SOFIA Science Center, NASA Ames, USA</td>
</tr>
<tr>
<td>Ellen Zweibel</td>
<td>University of Wisconsin, USA</td>
</tr>
</tbody>
</table>
Stage 1: Field seeds
- Generation of seed fields by Biermann battery, Weibel instability, or plasma fluctuations ($B \approx 10^{-18}-10^{-9}$ G)
LARGE SCALE STRUCTURES

Optical

Magnetic field strength
LARGE SCALE STRUCTURES

z=4.3

Optical

Magnetic field strength
PEAK OF STAR FORMATION ACTIVITY

Optical

Magnetic field strength

z=1.6
Stage 2: Field Amplification

- Amplification of seed fields by turbulent gas flows, i.e. turbulent dynamo (B~10^{-5} G).
- Turbulence is driven by accretion flows, SN explosions, and galaxy formation.
Stage 3: Field Ordering
- B-field ordered (stretched) by shear and by mean-field dynamo (a.k.a. differential rotation) ($t \approx 10^9$ yr, $B \approx 10^{-3}$ G)
- Turbulence driven by SN explosions and magnetorotational instabilities in galaxy disks.
TURBULENT DYNAMOS

Turbulent cascade (Dissipation)

B-field amplification (electromagnetic induction)

Turbulent coherent length of ~50-100 pc driven by SN explosions in spiral galaxies (e.g. Haverkorn 2008, Brandenburg & Subramanian 2005)
OPEN QUESTIONS

- How did the evolution of galaxies in mergers affect magnetic fields?

- Is the circumgalactic medium magnetized?

- How has the magnetic field been amplified by interaction/SF in galaxies?

- What is the structure of the magnetic field around an active nucleus?
SURVEY OF MAGNETIC FIELDS IN GALAXIES WITH SOFIA (SALSA)

GOAL:

First comprehensive study of the B-fields in the multi-phase ISM of nearby galaxies as a function of gas dynamics and galaxy types from hundred- to kpc-scale galactic environments.
SURVEY OF MAGNETIC FIELDS IN GALAXIES WITH SOFIA (SALSA)

GOAL:
First comprehensive study of the B-fields in the multi-phase ISM of nearby galaxies as a function of gas dynamics and galaxy types from hundred- to kpc-scale galactic environments.

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<thead>
<tr>
<th>ISM Phase</th>
<th>Instrument</th>
<th>Tracers</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dense and cold</td>
<td>FIR/HAWC+/SOFIA</td>
<td>Continuum dust total/polarized emission of aligned dust B-field orientation</td>
</tr>
<tr>
<td>Warm and diffuse</td>
<td>Radio/VLA/Effersberg</td>
<td>Synchrotron emission B-field orientation/direction/strength</td>
</tr>
<tr>
<td>Molecular gas (CO)</td>
<td>Sub-mm/ALMA</td>
<td>Line emission morphology Velocity field</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Velocity dispersion (turbulent kinetic energy)</td>
</tr>
<tr>
<td>Neutral gas (HI)</td>
<td>21cm (varios telescopes)</td>
<td>Line emission morphology Velocity field</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Velocity dispersion (turbulent kinetic energy)</td>
</tr>
</tbody>
</table>
KEY SCIENCE TOPICS OF THE LEGACY PROGRAM

Active Galaxies

Star Formation

Galaxy Dynamo Theory

Interacting Galaxies

Intergalactic medium, galactic winds, energetic particles

Lopez-Rodriguez et al. 2020
Lopez-Rodriguez et al. 2021c
Borlaff et al. 2021
Lopez-Rodriguez 2021b
Lopez-Rodriguez 2021a

http://galmagfields.com/
Ordered mean-field dominates (galactic dynamo)

Large-scale B-field

Small-scale B-field

Spiral galaxy

NGC1068

HAWC+ (89 um)

M51

HAWC+ (154 um)

ORDERED MEAN-FIELD DYNAMO

Lopez-Rodriguez et al. 2020

Borlaff et al. 2021
M51
SPIRAL GALAXY WITH COMPANION

- Far-IR and radio do not necessarily trace the same B-field component along the LOS

Borlauff et al. 2021
RADIO AND FIR OBSERVATIONS TRACE DIFFERENT GALACTIC SCALE HEIGHTS

Radio

$h \sim 1-2$ kpc

Krause et al. (2018, 2020)
RADIO AND FIR OBSERVATIONS TRACE DIFFERENT GALACTIC SCALE HEIGHTS

Radio

$h \sim 1-2 \text{ kpc}$

Krause et al. (2018, 2020)

FIR

$h < 0.5 \text{ kpc}$

Jones et al. (2020) FWHM (HAWC+): 13.6”
B-field amplification due to galaxy interaction and/or star formation activity

Borlaff et al. 2021
Fletcher et al. 2011

Fletcher et al. 2011
Borlaff et al. 2021
Ordered mean-field dominates (galactic dynamo)

Large-scale B-field

Small-scale B-field

Spiral galaxy

NGC1068

Lopez-Rodriguez et al. 2020

Fluctuation dynamo dominates (SF, galaxy interaction)

Large-scale B-field

Small-scale B-field

M51

Spiral + Interaction

Borlaff et al. 2021
CENTAURUS A
MERGER GALAXY AND ACTIVE NUCLEI

- Distorted B-field across the warped disk.
- B-field arises from fluctuation dynamos.
- Large turbulence kinetic energy and fast rotating disk.

Leslie Proudfit, SOFIA

Lopez-Rodriguez (2021b, Nature Astronomy)
B-FIELD AMPLIFICATION DUE TO TURBULENCE DYNAMO DRIVEN BY MERGER

Ordered mean-field dominates (galactic dynamo)

Fluctuation dynamo dominates (SF and galaxy interaction)

Large-scale B-field

Small-scale B-field

Spiral galaxy

NGC1068

M51

Spiral + Interaction

Centaurus A

Remnant of a merger between elliptical and spiral galaxies

Lopez-Rodriguez et al. 2020

Borlaff et al. 2021

Lopez-Rodriguez 2021b
Polarization arising from synchrotron emission. Magnetized bar due to remnant galactic dynamo. Hints of helical B-field in the starburst region.
B-FIELD TRACED BY RADIO AND FIR POLARIMETRIC OBSERVATIONS

FIR (89 um)

Radio (18 and 22 cm)

Adebahr et al. (2017)
FIR POLARIZATION TRACES THE B-FIELD ALONG THE OUTFLOW AND DISK

Adebahr et al. (2017)

Radio (18 and 22 cm)

FIR (89 um)

Outflow

Galactic B-field

1.0 kpc

Dec. (2000.0)

42'00''

41'00''

40'00''

39'00''

3

2

1

Size in kpc

0.0 0.5 1.0

R.A. (2000.0)

Adebahr et al. (2017)
LARGE-SCALE FLOW ALONG THE GALACTIC OUTFLOW

U_0 \text{ (large-scale flow)}

\text{Observed B-field using HAWC+}

B \text{ (large-scale)}

\text{Turbulence}

B'_{DCF} = B_{DCF} \left|1 - \sigma_{\phi} \frac{U_0}{\sigma_v}\right|

\text{If } U_0 = 0: \text{ no large-scale flow (classical DCF method)}

\text{If large-scale flow dominates} \rightarrow B_{DCF} \text{ overestimates the B-field strength}

\text{If turbulence dominates} \rightarrow B_{DCF} \text{ underestimates the B-field strength}
TURBULENT MAGNETIC AND KINETIC ENERGIES ARE IN CLOSE EQUIPARTITION

Energy budget:
- The entrainment between kinetic, thermal, and magnetic energies are defined by the beta parameter: \( \beta' = \frac{U_K + U_H}{U_B} \)
Turbulent dynamo

Mergers
B-field amplification

SN explosions
Permeate IGM with B-fields

Interaction, SF, galactic dynamo
SF disturbs/amplify mean-field

Mean-field dynamo
Saturated B-field close equipartition with turbulent kinetic energy in the ISM
All galaxies have available radio polarimetric observations, molecular and neutral gas maps, and Herschel observations.

<table>
<thead>
<tr>
<th>NAME</th>
<th>TYPE</th>
<th>DISTANCE (Mpc)</th>
<th>HAWC+ EXIST</th>
<th>HAWC+ REQUEST</th>
<th>ON-SOURCE TIME (h)</th>
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<tr>
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<td>STDDEV</td>
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<td>5.8</td>
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</tbody>
</table>

Data available at:
Legacy Program website (high-level data products):
http://galmagfields.com/
First Data Release
14 galaxies
Starbursts
First Data Release

14 galaxies

AGN  Starbursts
First Data Release

14 galaxies

AGN  Starbursts  Spirals
STUDENTS AND SUMMER INTERNS

Iñigo Valenzuela Lombera + Susan Clark
Stanford Graduate Student
Physics

Magnetic field directions of spiral galaxies

William Jeffrey Surgeny + Susan Clark
Stanford Undergrad.

EB decomposition of B-field in spirals

Ifdita Hasan Orney
Stanford Undergrad.
Computer Science
Summer Intern 2022

Voronio algorithm applied to polarization

Abraar Salem
San Francisco State University
Physics
Cal-Bridge Program, Summer 2022

B-field orientation of starbursts
**POSTDOCS AND RESEARCHERS**

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NASA Postdoctoral Program
NASA Ames

**Lucas Grosset**
Postdoctoral Fellow

**Sergio Martin Alvarez**
Postdoctoral Researcher
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**Sarah Eftekharzadeh**
Instrument Scientist
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**Ignacio del Moral Castro**
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Instituto de Astrofisica de Canarias

M51 (Paper I)
B-field and kinematics
Data analysis tools

B-field vs. Rotational support in M83

B-field morphology of Circinus

MHD Simulations of galaxies

B-fields of the Unusual NGC 4736
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Join Stanford in Sep. 2022

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Sarah Eftekharzadeh
Instrument Scientist
SOFIA

B-fields of the Unusual NGC 4736

Ignacio del Moral Castro
PhD. Since Feb. 2022
Instituto de Astrofísica de Canarias

B-field vs. Rotational support in M83
STAY TUNED FOR MORE RESULTS

EXTRAGALACTIC MAGNETISM WITH SOFIA
(LEGACY PROGRAM)

http://galmagfields.com/