Astrophysics from Antarctica

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Ocean
Atmosphere

Earth sciences

Integrated System Science

Glaciology

Organisms and Ecosystems

Astronomy, Astrophysics, and Geospace

Instrumentation and Facilities
Stations

Year-round: 43
18 at Antarctic Peninsula
25 over the Continent

Seasonal: 62

Total population:
Winter <1000
Summer ~4000

Astrophysics from Antarctica
Antarctic Treaty System defines Antarctica as all of the land and ice shelves south of 60°S latitude

- Signed December 1, 1959 by 12 countries (IGY participants, 1957-1958)
- Entered into force in 1961... many nations joined... now 53 members

Important Treaty Provisions:

- Antarctica shall be used for peaceful purposes only (Art. I)
- Freedom of scientific investigation in Antarctica and cooperation toward that end ... shall continue (Art. II)
- Scientific observations and results from Antarctica shall be exchanged and made freely available (Art. III)
- The treaty does not recognize, dispute, nor establish territorial sovereignty claims; no new claims shall be asserted while the treaty is in force (Art. IV)
U.S. Antarctic Program on a global scale
Changing ice sheets
WAIS ice mass loss and sea level rise
How much, how fast?

Antarctic biota: Evolution and adaptation
Decoding genomics/transcriptomics
NSF Big Idea: “Rules of Life”

How did the Universe begin?
Next generation cosmic microwave background program
NSF Big Idea: Windows on the Universe
Where are we?

Snow runway

U.S. Amundsen-Scott South Pole Station
2.9 km elevation above sea level

IceCube Lab

ARA & ARIANNA testbeds

IceCube area

MAPO with BICEP Array

IceCube Lab

MAPO with BICEP Array

DSL w/BICEP3 & SPT
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1/1/2019
~10 m/year, ~1.1-km since Amundsen & Scott arrivals in 1911/1912

1/1/1912

South Pole Markers Line
Antarctic Neutrino Astrophysics

- **IceCube Neutrino Observatory** 10+ years of observation
  
  $272M MREFC Project, 2002-2010; M&O support (since 2008 to 2021; $7M/year) and science awards (~$3M/year) - jointly funded by GEO/OPP and MPS/Physics. 
  Lead PI: Francis Halzen, Univ. of Wisconsin-Madison and IceCube Collaboration (46 institutions, 12 countries) 
  NSF provides ~60% of the total M&O support

- **Askaryan Radio Array (ARA) concept for GZK neutrino studies**
  (5 testbed stations) 2012-2019  
  Jointly funded by OPP & PHY (~$350K/year)  
  Lead PI: Albrecht Karle, Univ. of Wisconsin (Collaboration of 5 institutions, two countries)

- **Antarctic Ross Ice-Shelf ANtenna Neutrino Array (ARIANNA)** concept for GZK neutrino studies 
  (7 testbed stations) 2010-2019  
  Jointly funded by OPP & PHY (~$175K/year)  
  Lead PI: Steven Barwick, Univ. of California-Irvine
Antarctic Astronomy & CMB Astrophysics

- **South Pole 10m CMB Telescope (SPT)**  
  12+ years of observation  
  2007-2019  
  Jointly funded by OPP & MPS/PHY/AST (~$2.7M/year)  
  Lead PI: John Carlstrom, University of Chicago & SPT collaboration (2 National Labs and 10 institutions, 3 countries)

- **BICEP** – Background Imager for Cosmic Extragalactic Polarization  
  13+ years of observation, 2006-2019  
  Array of up to 50-cm aperture telescopes; Jointly funded by OPP/PHY/AST (~$1.5M/year);  
  Lead PI: John Kovac, Harvard University & BICEP Collaboration (9 institutions, 4 countries)

- **HEAT** – Terahertz Robotic Telescope at Ridge A, 4.1 km elevation  
  6 years of observations, 2011-2016, removed from Antarctica in January 2019  
  Jointly funded by OPP & AST ($250K/year)  
  Lead PIs: Craig Kulesa (University of Arizona) and Michael Ashley (University of New South Wales, Australia)

- **NASA Long-Duration Balloon Program at McMurdo**  
  1990–2019  
  56 science payloads launched, 7 OPP co-funded, ~90% astrophysics

Σ ~ $4.5M/year
Energy and wavelength spectra versus distance of the visible Universe
About a fifth of the Universe cannot be explored using photon-based telescopes
IceCube Neutrino Observatory (ICNO) managed by OPP & PHY

- **IceCube was completed in 2010** as a discovery instrument - built to search for very high energy neutrinos created in most extreme cosmic environments
- **2013**: ICNO discovered first high energy (100 TeV – 10 PeV) cosmic neutrinos - over 100 high-energy events are currently collected... robust statistics!
- **Sep 22, 2017**: IceCube issued an alert 170922A upon pinpointing an extra-galactic neutrino (~0.3 PeV) source within 0.1° of the flaring blazar TXS 0506+056
July 12, 2018
NSF Press Release 18-050
Neutrino observation points to one source of high-energy cosmic rays
ICNO Mid-Scale Upgrade

Title: IceCube extension for precision neutrino physics and astrophysics (funded by PHY & OPP in 2018 for 60 months)

PI: Kael Hanson, Univ. of Wisconsin & 7 institutions, 4 countries

NSF: $23M  Other U.S. & Non-U.S. institutions: $13M in-kind

Additional 7 strings (each 100+ DOMs) in the center of DeepCore Array

Main Science Objective: Multimessenger Astrophysics - A new Window on the Universe

Science Topics:

✓ Tau neutrino appearance and the unitarity of the PMNS matrix

✓ Neutrino oscillations, sterile neutrino, and indirect Dark Matter detection

✓ Improving IceCube’s capabilities for neutrino astronomy:
  • Tau neutrino appearance on cosmic baselines
  • Neutrino astronomy with high-energy cascades
OPP & PHY – Askaryan Radio Array concept

Signal attenuation length at South Pole:
Optical: 150 m - 250 m
Radio: 1500 m

Detection method: Radio signal from secondary particles generated by an ultra-high energy (GZK, $>10^{18}$) neutrino interaction within the Ice

Concept: Full ARA array (37 stations, $\sim$100 km$^2$) may reach required sensitivity at the energies above 100 PeV
**Opp & Phy - Arianna Concept**

- **Concept**: An array of ~1000 autonomous stations on the snow surface in Antarctica to measure a flux of ultra-high energy (GZK) neutrinos from astrophysical sources.
- **Same as ARA’s radio detection method** that additionally includes measurements of a signal reflected from the water surface under the Ross Ice Shelf.
- **Currently testing two Arianna stations at the South Pole Station** – to compare data with ARA data.

Testbed: 7 stations in a hexagonal array, 1-km spacing; deployed over Ross Ice Shelf, ~100-km south of McMurdo.


First detection of cosmic rays’ radio signal by this self-triggered array.
South Pole Telescope Science

13th year in operation, three cameras, ~200 papers on vast array of subjects, over 10,000 citations

First Generation:
The SPT-SZ Camera
- 2007-2011
- 960 detectors, 3 bands
- 2500 deg² survey to 18 μK-arcmin

Second Generation:
The SPTpol Camera
- 2012-2016
- 1536 detectors, 2 bands, polarization sensitivity
- 500 deg² survey to 5 μK-arcmin

Third Generation:
The SPT-3G Camera
- Next slide

SPT discoveries include some of the most extreme objects in the Universe and have had lasting impacts on the fields of cosmology, galaxy clusters, and high-redshift galaxies.

SPT citations by subject

SPT publications and citations span many sub-fields of astronomy and physics

Massive Primordial Galaxies Found Swimming in Vast Ocean of Dark Matter

Hanson et al. (2013)
McDonald et al. (2013)
Marrone et al. (2018)
SPT-3G Camera

Third Generation:

- 16,000 polarization-sensitive detectors in three frequency (95, 150, 220 GHz) bands
- Order-of-magnitude improvement over SPTpol and other 2015-era CMB cameras
- Maps a 3x larger region than SPTpol to full 4-year-survey SPTPol depths in 1 year
- Currently surveying the final target sky field, a 1500 deg² region fully overlapping the BICEP Array survey field (for de-lensing the B-mode signals)
- Final target map depth (2.2 μK-arcmin at 150 GHz) and observing strategy will enable breakthrough science in many areas, including new windows on the transient Universe and multi-messenger astrophysics

http://pole.uchicago.edu
Using the Atacama Large Millimeter/submillimeter Array (ALMA), an international team of scientists has uncovered a startlingly dense concentration of 14 galaxies that are poised to merge, forming the core of what will eventually become a colossal galaxy cluster.

Known as a protocluster designated as SPT2349-56, it is located approximately 12.4 billion light-years away and it was first discovered as a faint smudge of the mm-wavelength light in 2010 with the NSF’s South Pole Telescope.

Current theory and computer models suggest that protoclusters as massive as the one observed by ALMA, however, should have taken much longer to evolve.

Zooming in to the galaxies discovered by ALMA that are evolving into a galaxy cluster

The middle image -- a portion of a much-wider survey by NSF's South Pole Telescope -- uncovered the distant galactic source that was studied by ALMA to reveal the 14 galaxies

The outer field is from data taken by the Hershel Space Observatory

Credit: ALMA (ESO/NAOJ/NRAO), T. Miller & S. Chapman et al.; Herschel; South Pole Telescope; (NRAO/AUI/NSF) B. Saxton
Astronomers Capture First Image of a Black Hole

Paradigm-shifting observations of the gargantuan black hole at the heart of distant galaxy Messier 87

M87* is located in the Virgo galaxies cluster about 55 million light years from Earth
Deep CMB field observations from South Pole

**Keck Array** - Hardware upgrades in 2018/19 included receivers optics with new hybridized focal plane

**Full-scale CMB Stage 3 program** replaces the Keck Array (95-270 GHz) with BICEP Array (next season 30 & 40, then 95, 150, 220 & 270 GHz) for the deep foreground separation

**With the SPT-3G delensing**, plans are to reach $\sigma(r) < 0.004$ by the end of 2021, and maybe $\sigma(r) \sim 0.002$ by 2023

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Total # of bolometers for Deep Field:
- BICEP3 + Keck Array: 6,000 (now)
- BICEP3 + BICEP Array: $\sim 35,000$ (next)
BICEP program: CMB/B-modes & progress on $\sigma(r)$

BICEP/Keck/Planck analysis
2014 BICEP/Keck analysis adds 95 GHz
$\sigma(r) = 0.034$

2015 BICEP/Keck analysis
$\sigma(r) = 0.025$

2016/17 BICEP/Keck + SPTpol delensing
$\sigma(r) = 0.019$
Phys. Rev. Lett. 121, 221301, 2018

2018/21 BICEP Array+SPT-3g delensing
$\sigma(r) = 0.010$
Coming in 2019
$\sigma(r) \sim 0.010$
Forecast

Raw sensitivity of this experiment to primordial B-modes (i.e., with no foregrounds or lensing) is close to $\sigma(r) \sim 0.006$

It is now all about components separation!
• The 0.6m aperture High Elevation Antarctic Terahertz (HEAT) telescope operated robotically at the Ridge A summit, delivering spectroscopic data (150 to 500 microns) for 6 years (2011-2016)

• This was a joint project of the U.S. and Australian scientists from the University of Arizona (HEAT telescope) and University of New South Wales (PLATO-R power module)

• The HEAT and PLATO-R were removed from Ridge A in January 2019

http://soral.as.arizona.edu/heat/

HEAT’s deep spectroscopic surveys (left) are finding pervasive, diffuse molecular clouds not seen in existing surveys of CO and HI (right)

http://mcba11.phys.unsw.edu.au/~plato-r/
• **1988** – First MoA was signed between NASA and NSF, planning to launch one (1) LDB payload every other year beginning January 1990

• **29 years later** - total 56 LDB and SPB payloads have been flown from McMurdo - in average 2 payloads per year!

• In 2018-2019 austral summer season, only two payloads (SuperTIGER & X-Calibur, out of three planned) were flown; both were terminated soon after being launched due to equipment failures. The BLAST payload is stored on-site and will be launched in austral summer 2019/2020

http://www.csbf.nasa.gov/antarctica/ice.htm
NSF’s current annual science funding (excluding logistical support) for Antarctic Astrophysics is ~$9.0M, where ~$5M go to neutrino astrophysics; ~$4M go to astronomy & CMB-related projects.

OPP co-funds almost all Antarctic astrophysical research projects together with MPS/PHY & AST science programs!

IceCube M&O and related projects (IceCube science, ARA, ARIANNA, etc.) are co-funded by OPP and PHY (50:50) since the IceCube MREFC project was built at South Pole.

Thus, the combined annual spending for Antarctic neutrino astrophysics reaches $10.5M; in 2004-2018, OPP and PHY spent jointly ~$120M.

Antarctic astronomy & CMB research are mostly funded by OPP. Since 2004, AST (PHY since 2012) helped co-funding some CMB projects. In 2018, the AST/MSIP & OPP/AAGS programs jointly co-funded (50:50) the latest BICEP Array award.

Thus, the combined annual spending for Antarctic astronomy and CMB research is currently about $5M; in 2004-2018, OPP, AST, and PHY spent jointly ~$100M.
Thank you for your attention!

Questions?