The Evolution of Space-Based Magnetometers: Scientific Discovery Engineering at its Best

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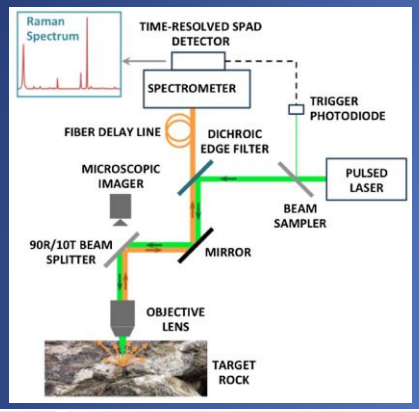
Jet Propulsion Laboratory
California Institute of Technology

Current Research

Time-Resolved Raman Spectrometer (TRRS)
PI: Jordana Blacksberg



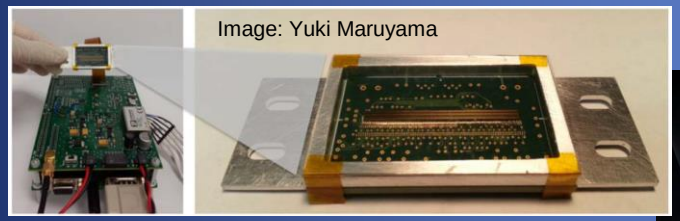


Image: Yuki Maruyama

Image: NASA, Curiosity Laser-Induced Breakdown Spectroscopy (LIBS)

Gas and Ice Spectrometer Radar (GAISR)
PI: Ken Cooner

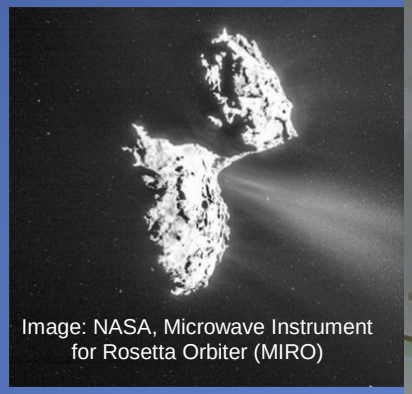


Image: NASA, Microwave Instrument for Rosetta Orbiter (MIRO)

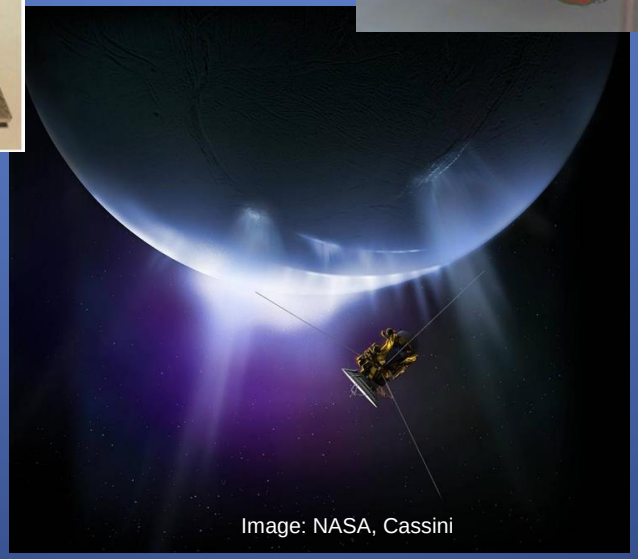
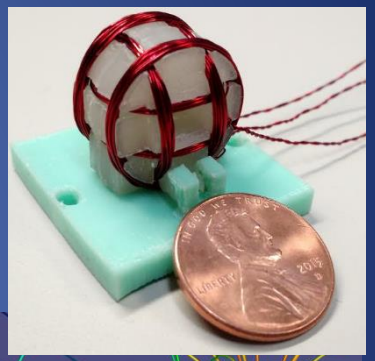


Image: NASA, Cassini

Silicon Carbide Magnetometer (SiCMag)
PI: Corey Cochrane



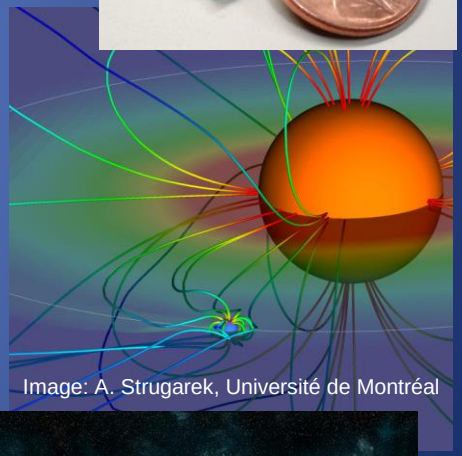


Image: A. Strugarek, Université de Montréal

Image: Marc Ward/Shutterstock

This Presentation

- The culture of engineering today can be heavily driven by scientific discovery, especially at the Jet Propulsion Laboratory.
- Ground breaking scientific discoveries are made there every day and are only accomplished through advances in engineering.
- At JPL, technology is constantly being pushed to its limits for the ultimate discovery, that being finding of life beyond Earth.
- Magnetic field measurements from a magnetometer are a fundamental key to this search, especially in reconnaissance missions to bodies we don't know much about because they have the ability to indirectly find water.
- This presentation will illustrate the capabilities of a magnetometer, their history in space and evolution including my current research in the field, and how they tie in with the culture of engineering.

Outline

Part I

Brief Overview of JPL

Part II

Magnetometry

Part III

Magnetometer in Space

Part IV

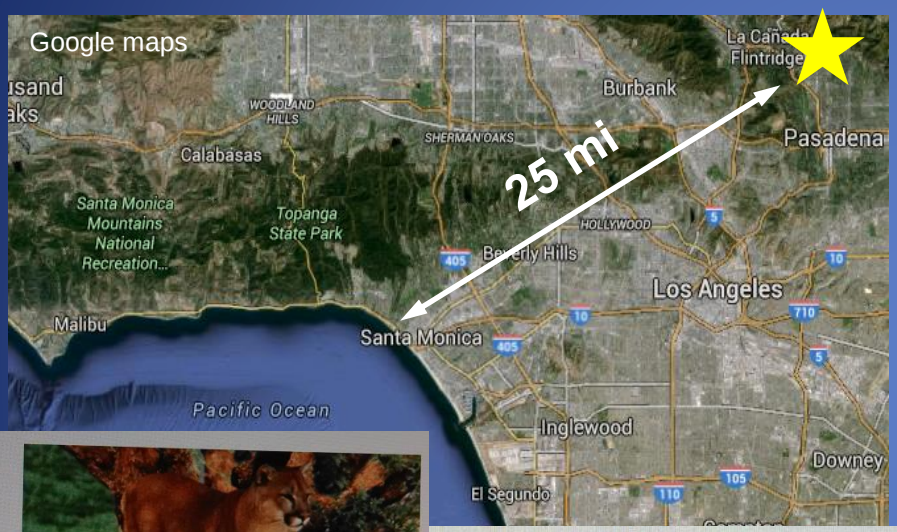
Solid-state SiC based magnetometer

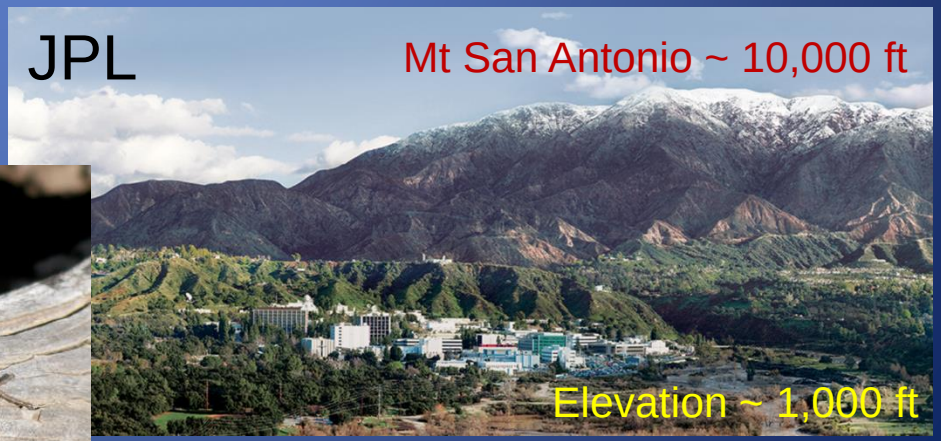
NASA Centers

ARC – Ames Research Center. Information technology, biotechnology, nanotechnology, aerospace operations ,rotorcraft, thermal
AFRC – Armstrong Flight Research Center. Aerodynamics, aeronautics flight testing, aeropropulsion, flight systems, thermal testing,
GRC – Glenn Research Center. Aeropropulsion, communications, energy technology, high-temperature materials research.
GSFC – Goddard Space Flight Center. Planetary science, LIDAR, cryogenic systems, tracking, telemetry, remote sensing, command.
JPL – Jet Propulsion Laboratory. Near- and deep-space, microspacecraft, space comm., information systems, remote sensing, robotics.
JSC – Johnson Space Center. Artificial intelligence and human-computer interface, human space flight operations, avionics, sensors, comm.
KSC – Kennedy Space Center. Fluids and fluid systems; materials, process engineering; command, control, and monitor systems;
LaRC – Langley Research Center. Aerodynamics, flight systems, materials, structures, sensors, measurements, information sciences.
MSFC – Marshall Space Flight Center. Materials, manufacturing, nondestructive evaluation, biotechnology, space propulsion, controls.
SSC – Stennis Space Center. Propulsion systems, remote sensing, nonintrusive instrumentation.

JPL Campus

JPL is located at the base of the Sn Gabriel Mountains in southern California and is run by the California Institute of Technology located in Pasadena.





What JPL Does

The primary focus of JPL is the robotic exploration of planetary systems

Explorer 1 - 1958

(Sputnik 1957)

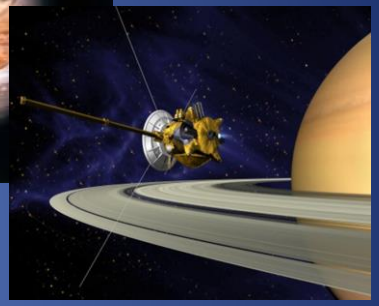
Voyager - 1977

Deep Space Network

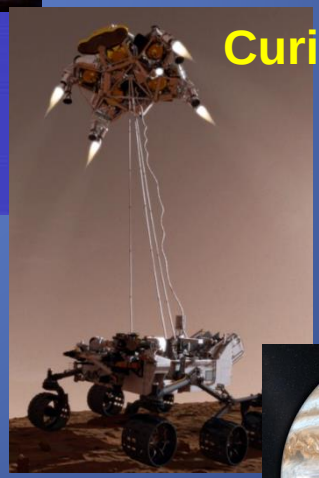
Spirit & Opportunity 2003

Galileo 1995

Cassini 2004



Curiosity 2012

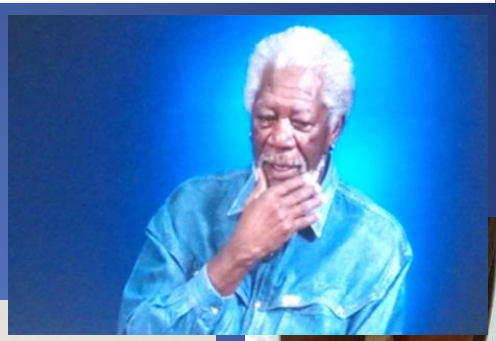


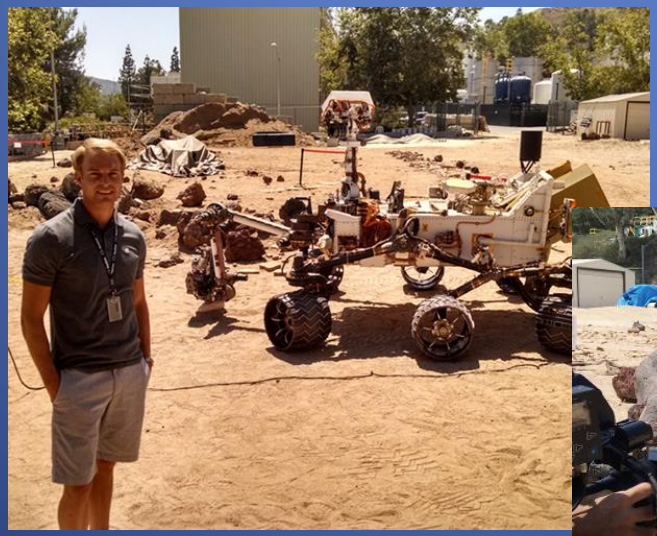
Robosimian

Juno 2016

Image source: NASA

I've got to meet and see some cool things!





Silicon Happy Valley, University Park, PA– Corey J Cochrane - 2016-04-18

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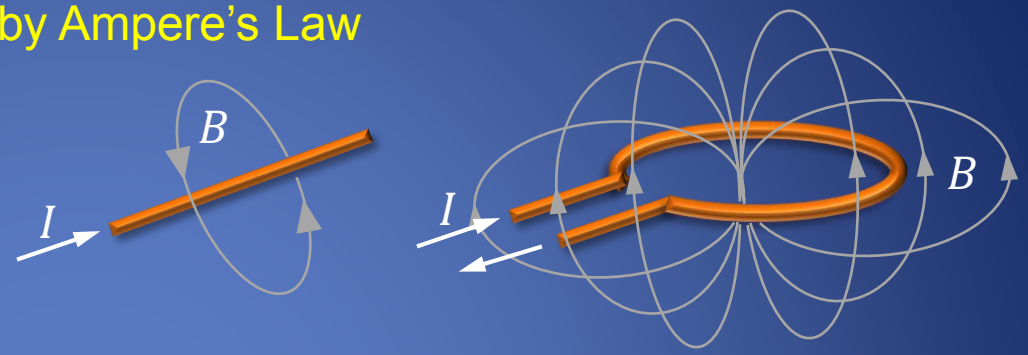
Origin of Magnetic Fields

1. Moving electric charge as described by Ampere's Law

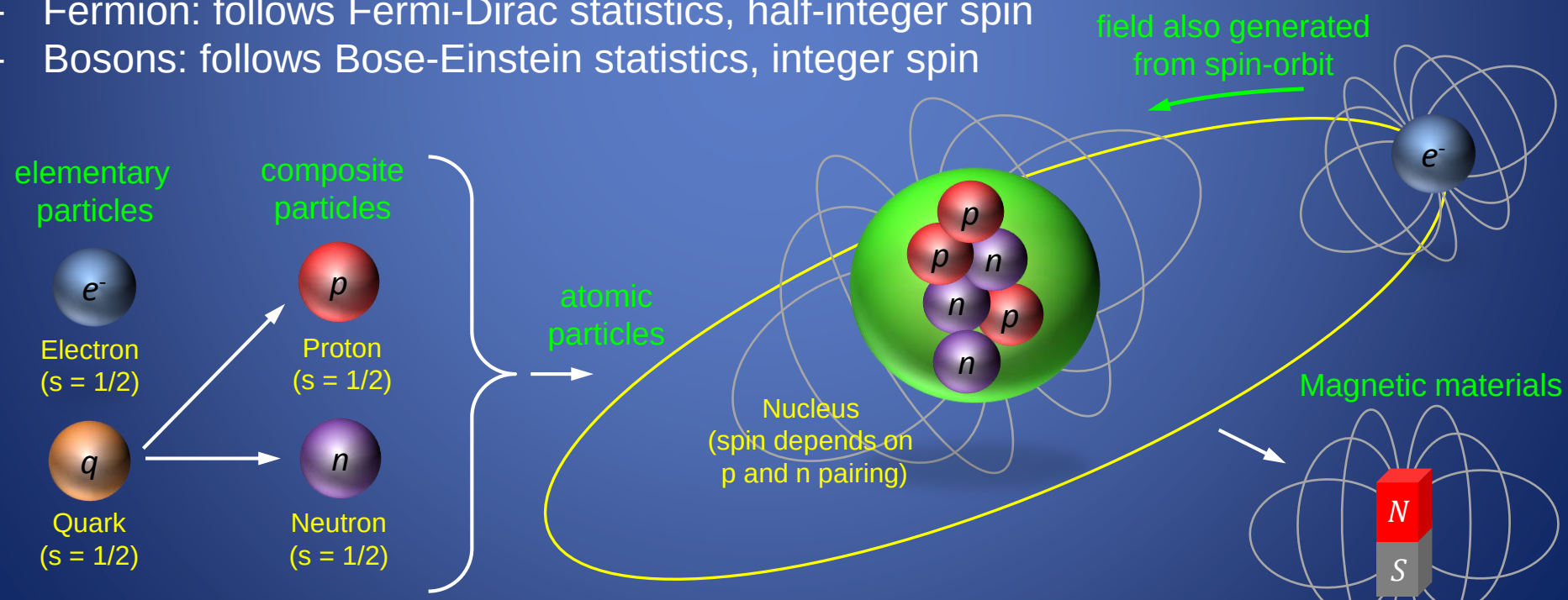
$$\oint B \cdot dl = \mu_0 \iint_S J \cdot ds = \mu_0 I$$

Integrated magnetic field along a closed loop is proportional to the current passing through that surface



2. Intrinsic angular momentum of subatomic particles due to spin:

- Fermion: follows Fermi-Dirac statistics, half-integer spin
- Bosons: follows Bose-Einstein statistics, integer spin



Magnetic Field Sensing on Earth

Navigation

Archaeology

Magnetic Resonance Imaging

Mineral Detection

Shipwreck Detection

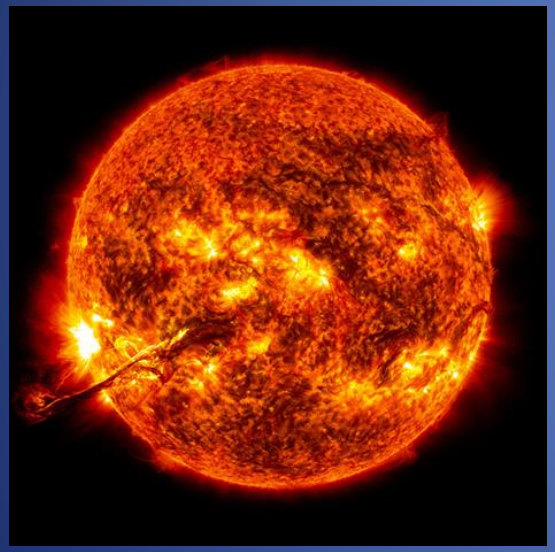
Submarine Monitoring

Magneto-encephalography

Treasure hunting!

Need for Magnetic Field Sensing in Space

Heliophysics



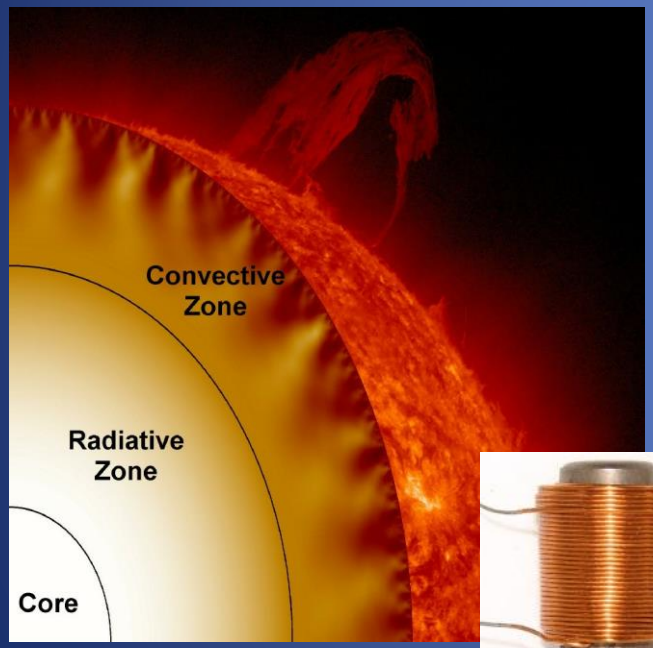
Earth Science

Planetary Science

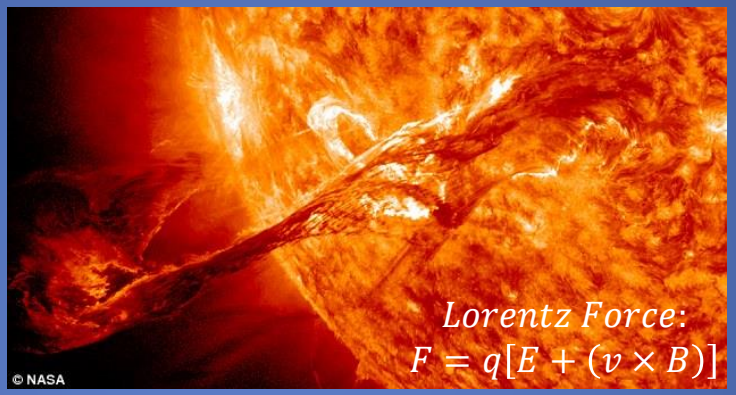
What type of science return is possible with a magnetometer?

Heliophysics

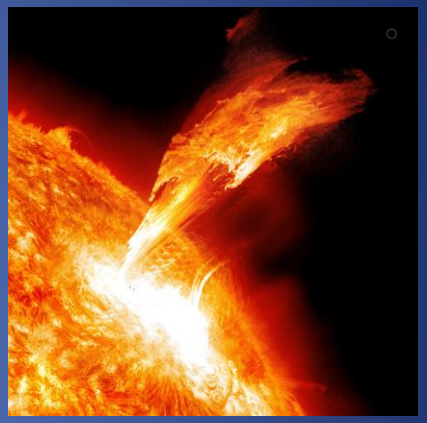
Solar dynamo
Magnetic field generated from currents flowing within the sun due to flow of ionized particles – Ampere's Law!



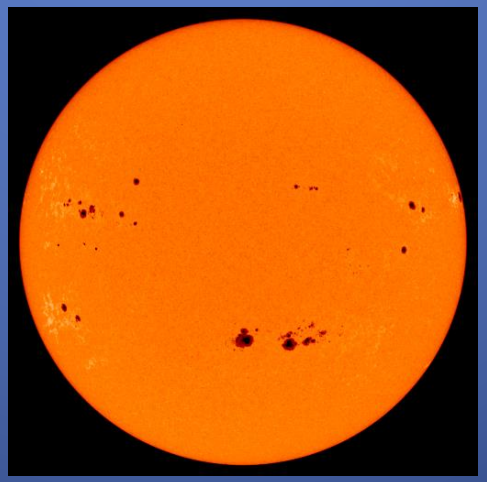
Solar prominence
Dense plasma held in place by magnetic field lines of the sun



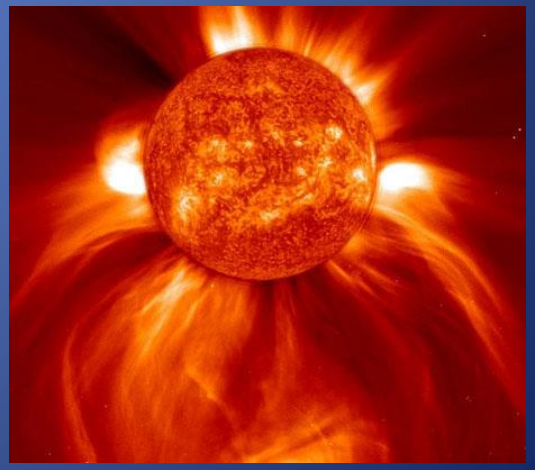
Solar flare
Magnetic reconnection



Sun spots



Interplanetary magnetic field (IMF) / Solar Wind

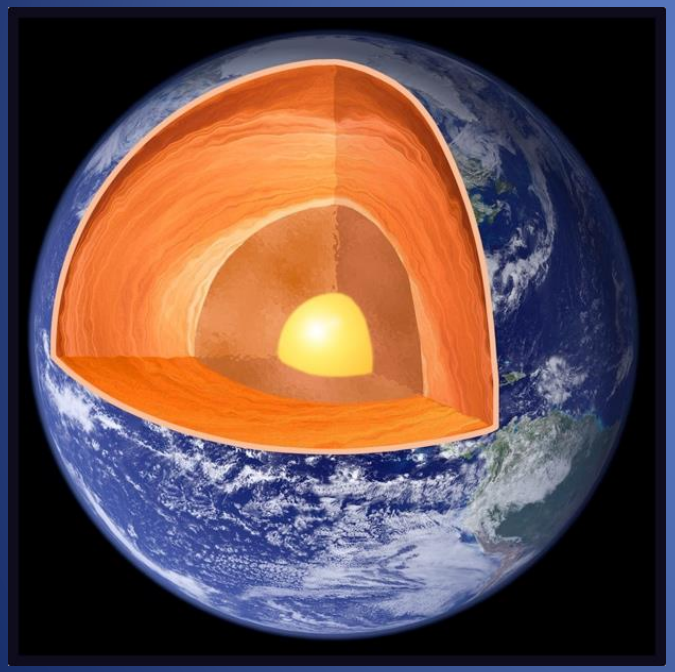


Images credit, NASA

Earth Science

Earth's Dynamo

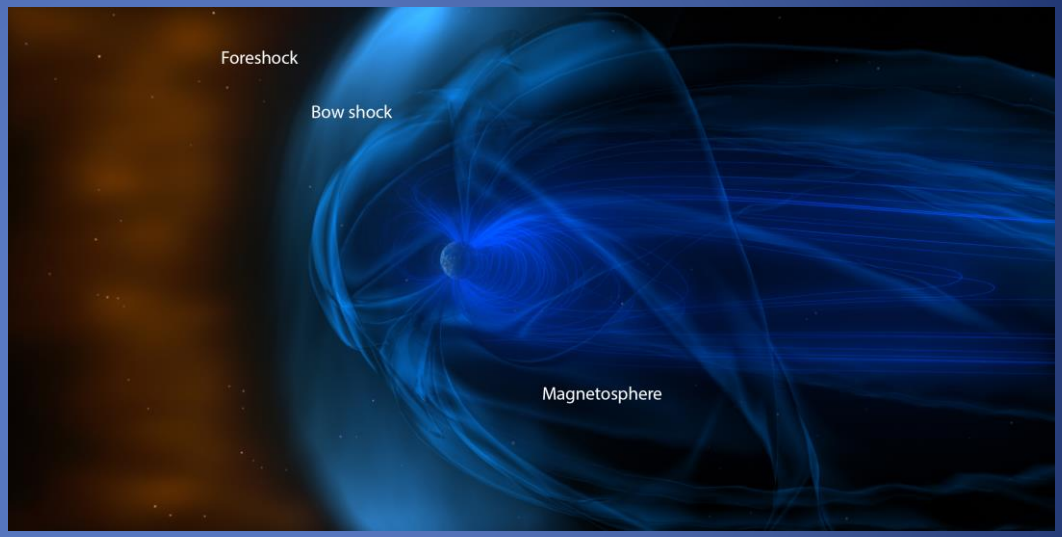
Magnetic field generated likely due to liquid flow around solid core (Fe or Ni) – an electromagnet! Combination of Earth's rotation, gravity, and convection mechanisms also play a role self-sustaining field generation.



Cannot be permanent magnet because too hot to be ferromagnetic!

Solar Wind Interaction

Ionized particles from the sun interact with Earth's magnetic field and atmosphere resulting in various currents which induce additional magnetic fields.

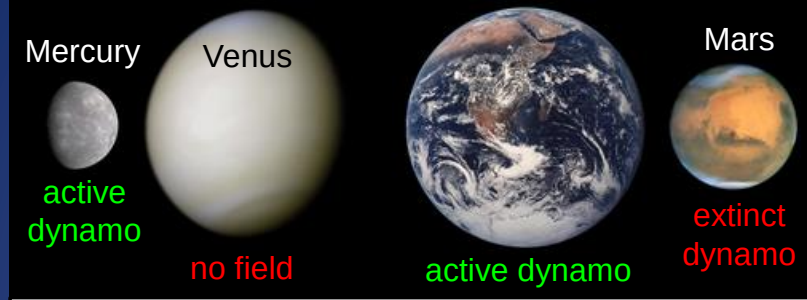


Aurora Borealis

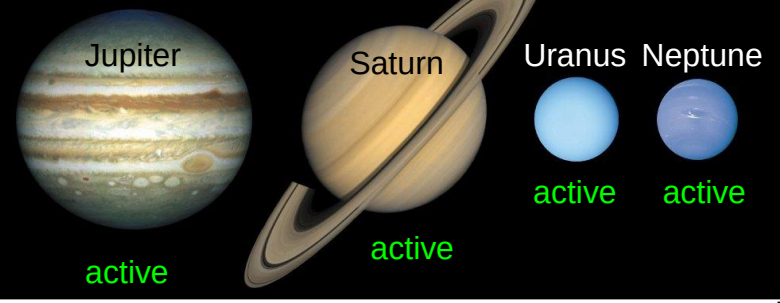
Charged particles spiral along magnetic field lines excite Oxygen and Nitrogen in the atmosphere giving off

Planetary Science

Magnetic Fields of Terrestrial Planets



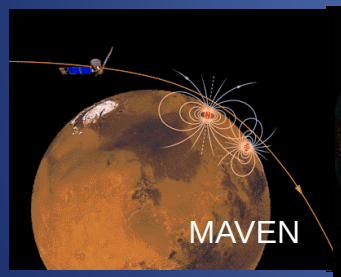
Magnetic Fields of the Gas and Ice Giants



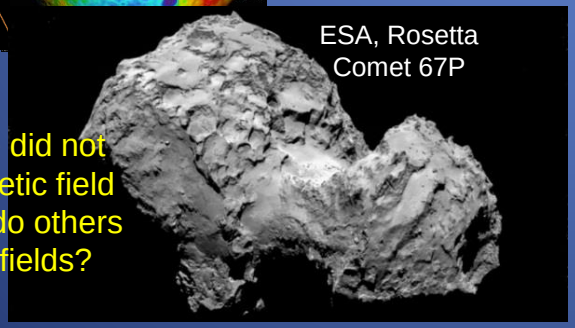
0.0033 G 2,439 km 0.01	< 0.00002 G 6,051 km < 0.0001	B_E = 0.31 G r_E^3 = 6,378 km $B_E r_E^3$ = 7.9 x 10^{10} G	< 0.000005 G 3,396 km < 0.0001	4.28 G 71,398 km 20,000	0.21 G 60,330 km 580	0.228 G 25,600 km 48	0.142 G 24,765 km 27	B_s r $B_s r^3 / B_E r_E^3$

http://nssdc.gsfc.nasa.gov/planetary/factsheet/

Crustal magnetic field anomalies provide magnetic history



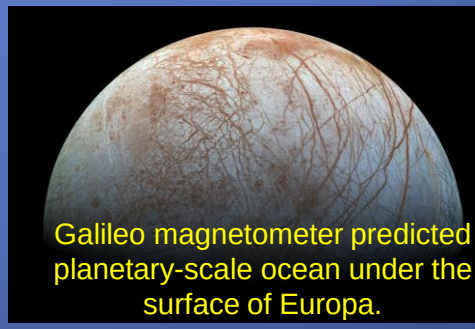
U.R. Christensen, et. al., Planetary Magnetism, Sptringer NY, 2010



Lander Philae did not detect a magnetic field on comet, but do others have crustal fields?

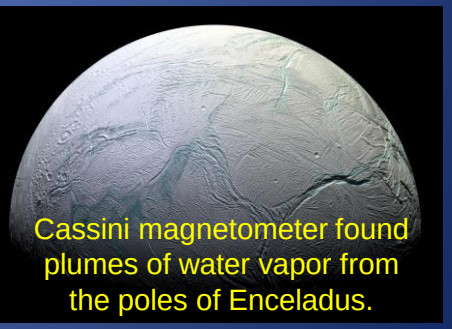
Magnetometers aid in the search for life

Europa/Jupiter



Galileo magnetometer predicted planetary-scale ocean under the surface of Europa.

Enceladus/Saturn



Cassini magnetometer found plumes of water vapor from the poles of Enceladus.

Images credit, NASA

What’s Next? Juno!

- *Goal:* **Improve our understanding of the solar system’s beginnings by revealing the origin and evolution of Jupiter.**

- *Objectives:*
- Determine how much water is in Jupiter's atmosphere, which helps determine which planet formation theory is correct (or if new theories are needed)

- Look deep into Jupiter's atmosphere to measure composition, temperature, cloud motions and other properties

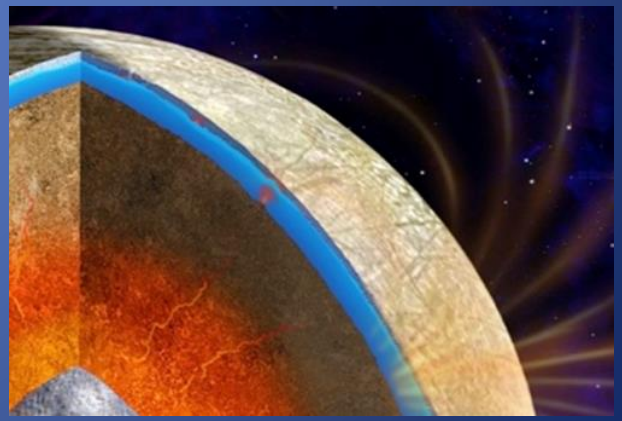
- Map Jupiter's magnetic and gravity fields, revealing the planet's deep structure

- Explore and study Jupiter's magnetosphere near the planet's poles

Source: NASA

What's After That? Europa!

- *Goal:* **Explore Europa to investigate its habitability**
- *Objectives:*
  - **Ice Shell & Ocean:** Characterize the ice shell and any subsurface water, including their heterogeneity, ocean properties, and the nature of surface-ice-ocean exchange
  - **Composition:** Understand the habitability of Europa's ocean through composition and chemistry
  - **Geology:** Understand the formation of surface features, including sites of recent or current activity, and characterize high science interest localities
  - **Reconnaissance:** Characterize scientifically compelling sites, and hazards, for a potential future landed mission to Europa



Source, Bob Pappalardo, JPL

ICEMAG

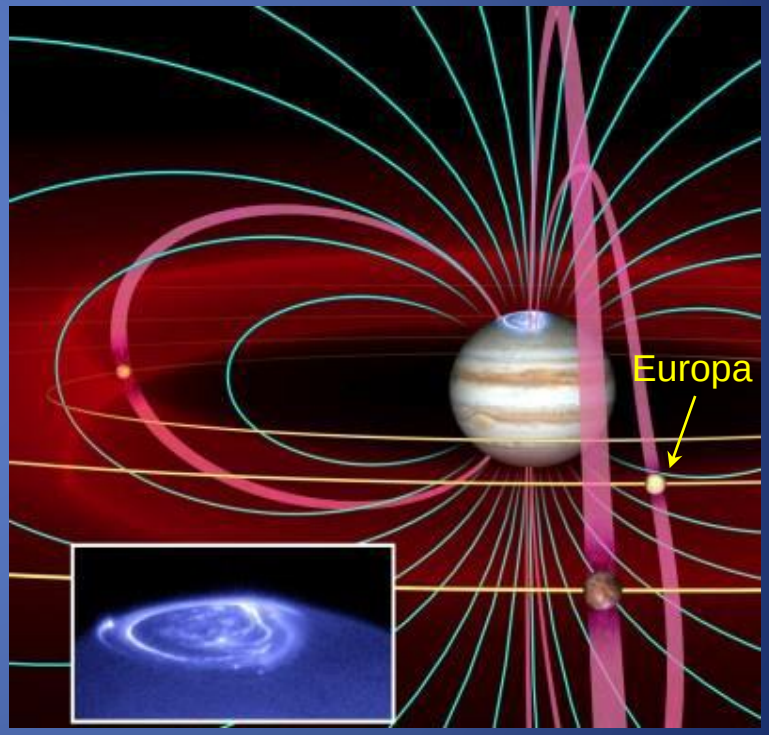
Interior Characterization of Europa using Magnetometry

PI: Carol Raymond, Jet Propulsion Laboratory (JPL)

ICEMAG would characterize the complex magnetic environment at Europa

Ocean parameters can be retrieved from induction response of Europa at multiple frequencies

- Determine the location, thickness, and salinity of Europa's ocean by magnetic field induction at multiple frequencies
- Identify sources of Europa's atmosphere and atmospheric loss processes by characterizing any active vents, plumes, and ionized plasma trails
- Understand coupling of Europa to Jupiter's ionosphere, and coupling of plumes to flowing plasma



Jupiter's magnetospheric field lines (blue), magnetic flux tubes of Io, Europa, Ganymede (pink), Io torus (red), auroral footprint (inset)

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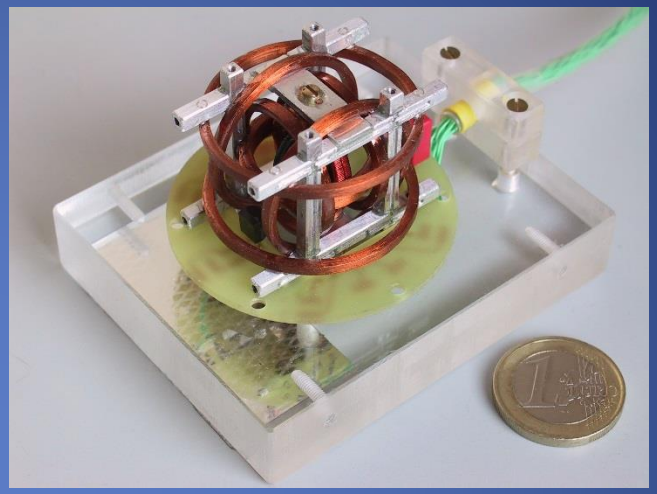
Solid-state SiC based magnetometer

Fluxgate Magnetometer

NASA/MAVEN



ESA/BepiColombo for Mercury

Application:
- Low-frequency fields (DC to 10's of Hz)
- Vectorized field sensing

Function: 3 coil design
- drive ferromagnetic core, sense induced field, and cancel field using 2nd harmonic as feedback

Sensitivity: $< 1\ nT/\sqrt{Hz}$

Stability: $< 1\ nT/\sqrt{Hz}$

Advantages: inexpensive, robust, good sensitivity, reliable

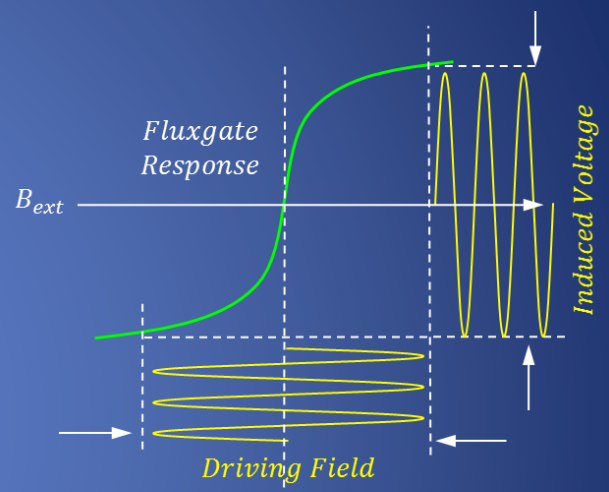
Disadvantages: larger footprint, not purely electrical, not great stability, requires 3 sensors to measure 3 components

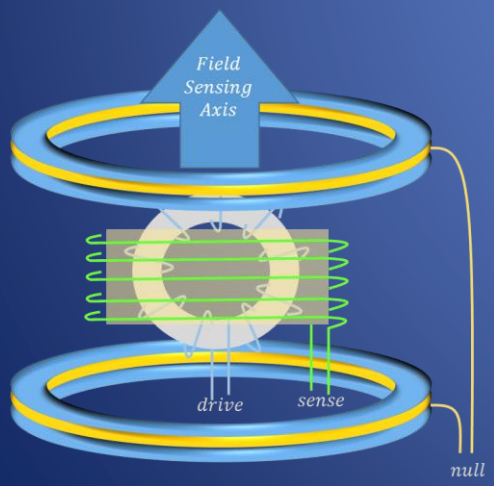
Missions:
- Mariner 2/5/10 (Venus 1962/1967/1973)
- Mariner 4 (Mars 1964)
- Pioneer 11 (Jupiter/Saturn/ISM 1973)
- Voyager 1/2 (Gas Giants/ISM 1977)
- Pioneer (12) Venus Orbiter (Venus 1978)
- Mars Global Surveyor (Mars 1996)
- Cassini (Saturn 1997)
- Messenger (Mercury 2004)
- Juno (Jupiter 2011)
- MAVEN (Mars 2013)

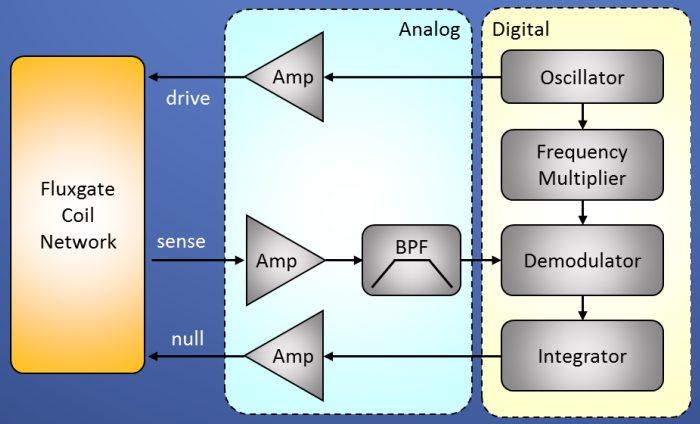
Fluxgate Operation

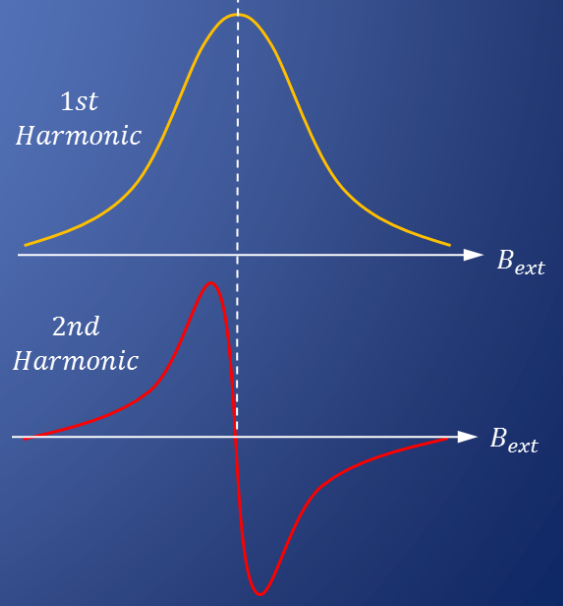
Three sets of coils around ferromagnetic core used for drive, sense, and field nulling

- AC drive field alternately saturates the ferromagnetic core
- Response is non linear so will be rich in harmonics
- In the absence of a field, only odd harmonics induced in sense coil
- If a field is present, even harmonics can be induced in sense coil
- Nulling coil is used to cancel the external field
- The nulling current gives the strength of the external field.



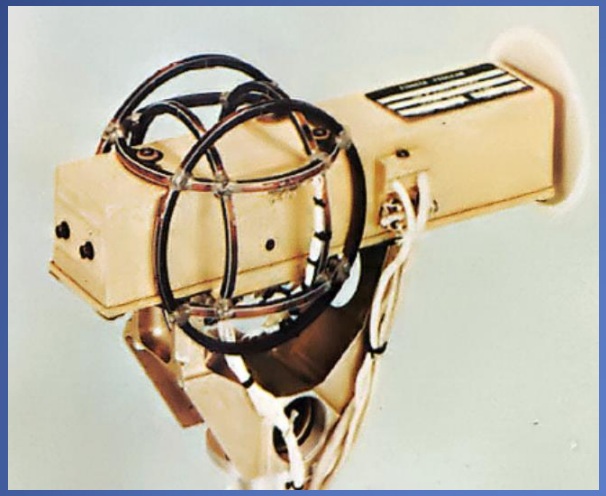




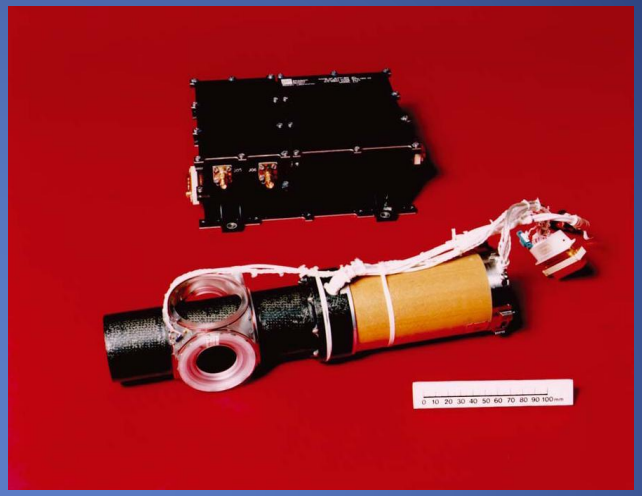


Optically Pumped Atomic Gas

NASA/JPL Pioneer 10/11



NASA/JPL Cassini



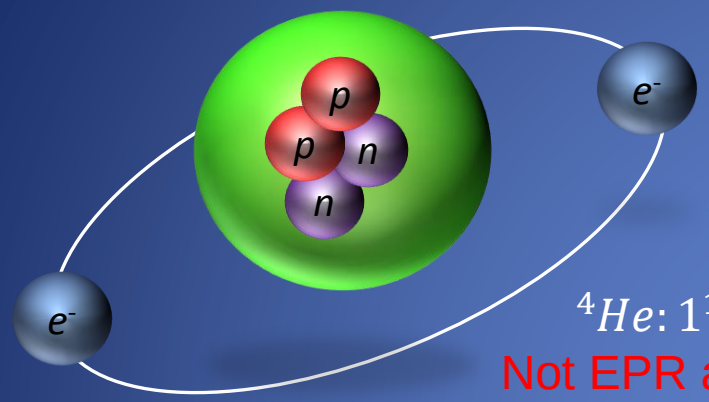
Application: Low-frequency fields (DC to 10's of Hz)
Function: optically pumped alkali and metastable ^{4}He
- Vectorized: rotating field varies pumping efficiency, photon absorption depends on field angle, demodulated harmonics used to cancel ambient field
- Scalar: Maintain pumping efficiency using EPR, Larmor precession frequency used to determine field

Sensitivity: $10's\ of\ pT/\sqrt{Hz}$
Stability: $< 10\ pT/\sqrt{Hz}$
Advantages: Very sensitivity, stable, scalar/vector modes
Disadvantages: Relatively expensive, higher power, larger footprint, not purely electrical, RF and optical components, need for resonance search

Missions:
- Mariner 4 (IMF between Earth/Mars 1964)
- Mariner 5 (IMF between Earth/Venus 1967)
- Pioneer 10 (Jupiter/ISM 1972)
- Pioneer 11 (Jupiter/Saturn/ISM 1973)
- ISEE-3 (Solar wind and Earth's atmosphere1978)
- Ulysses (Heliosphere 1990)
- Cassini Huygens (Saturn 1997)
- SAC-C (Earth 2000)
- SWARM (Earth 2013)
- Europa (ICEMAG)

Metastable ^{4}He

Need to operate in the Metastable ^{4}He regime (2 electrons in triplet state, 2 neutrons, 2 protons) obtained by RF excitation

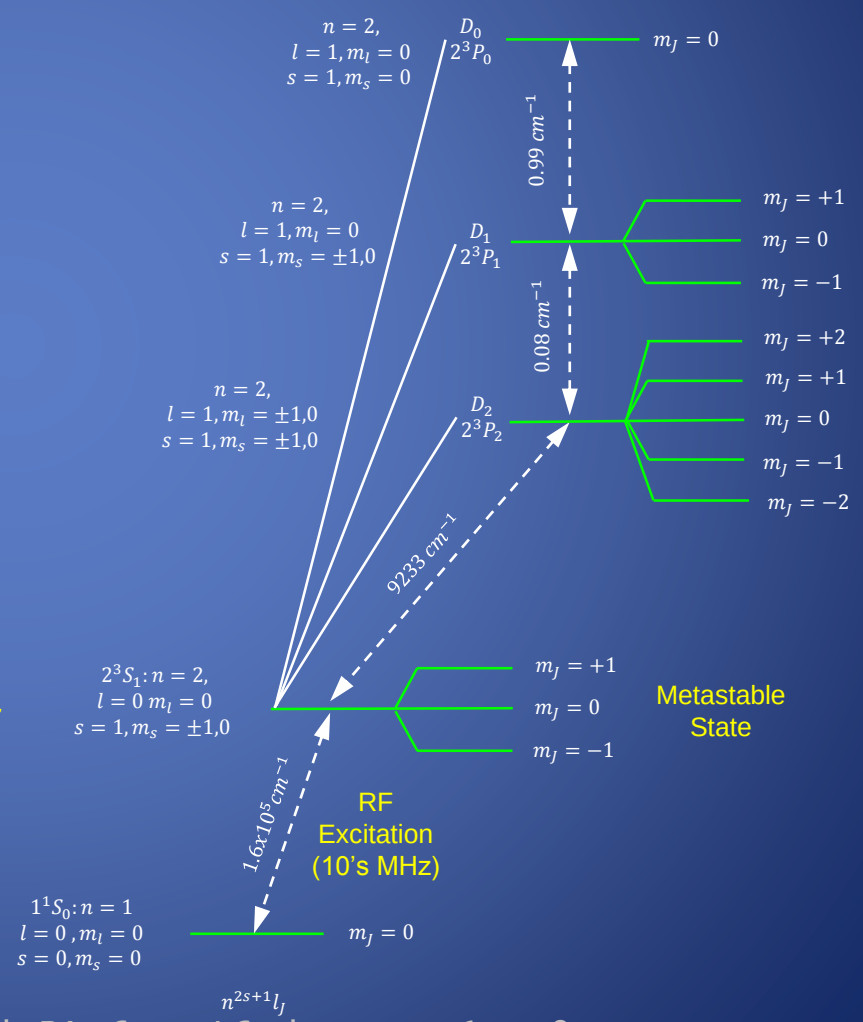


$^4He: 1^1S_0$

Not EPR active!

$$\text{total angular momentum}$$
$$J = S + L$$
$$\text{total projected angular momentum}$$
$$m_J = m_s + m_l$$

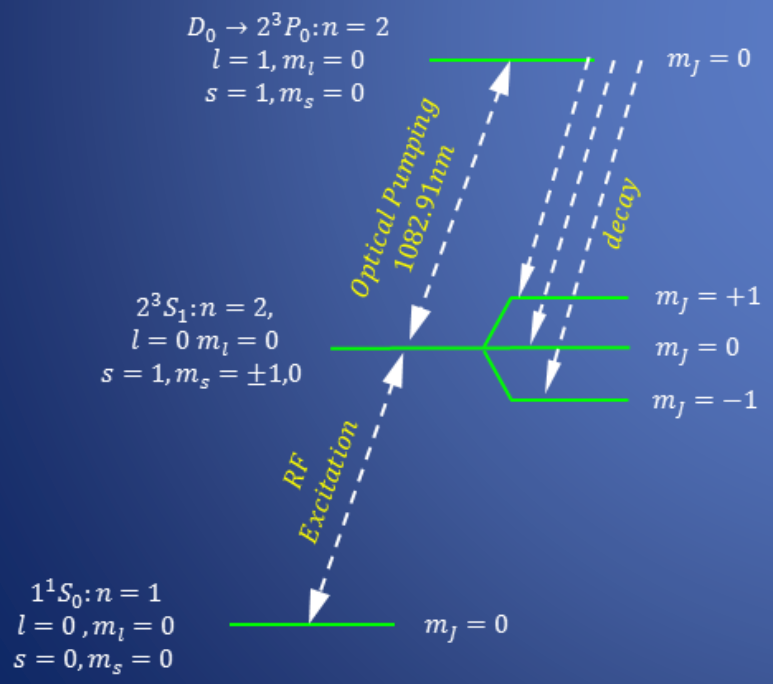
principal quantum number: n
orbital angular momentum: $l = 0,1, \ldots n-1 = s, p, d, f$
orbital angular momentum projection: $-l \leq m_l \leq l$
electron spin angular momentum: s
electron spin projection: $-s \leq m_s \leq s$

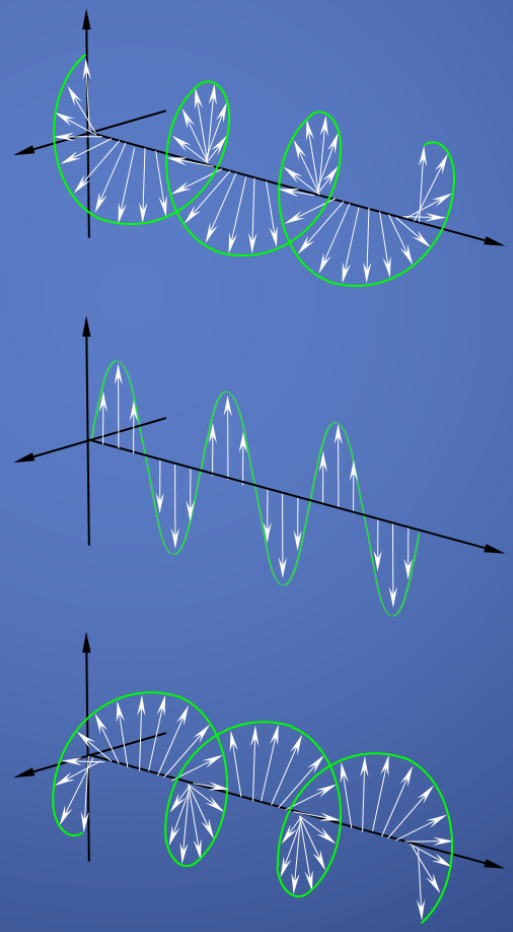


Optical Pumping

- 1083 nm laser light used to excite the metastable helium atoms to the D_0 level
- Circular polarizing filter typically used to depopulate either of the $m_J = \pm 1$ states
- Results in a magnetization aligned with or against the external magnetic field.

Absorption of photons only occurs if they have the proper discretized energy and angular momentum is conserved!





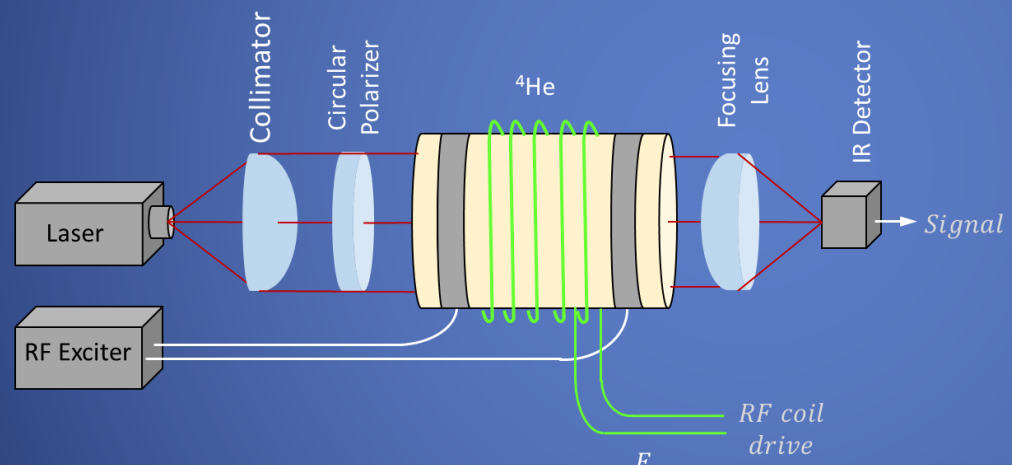
Right Hand Circularly Polarized
angular momentum: $-\hbar$
depopulates $m_J = +1$ states

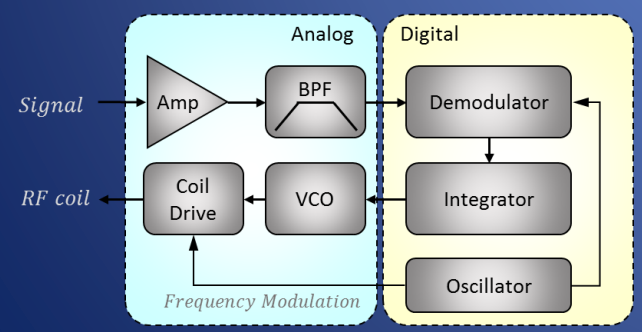
Linear Polarized
angular momentum: 0
depopulates $m_J = 0$ states

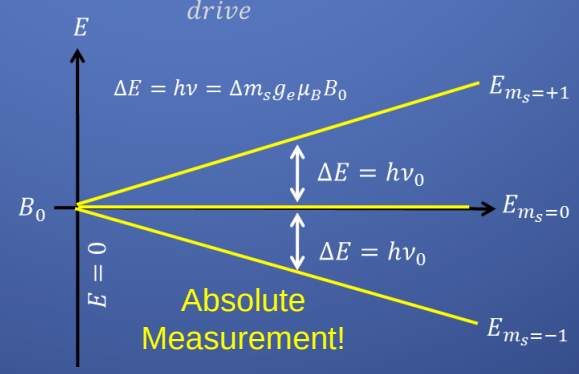
Left Hand Circularly Polarized
angular momentum: $+\hbar$
depopulates $m_J = -1$ states

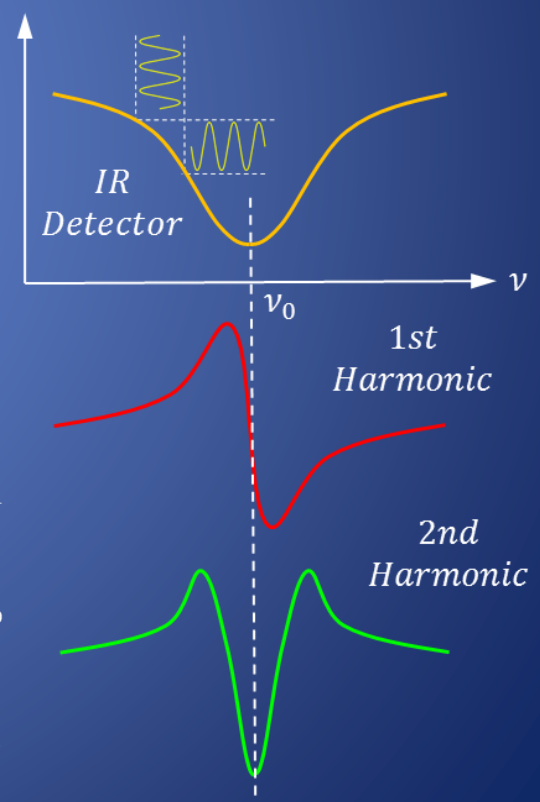
Scalar Mode

- Oscillating field B_1 applied at frequency ν to satisfy electron paramagnetic resonance.
- Repopulation of the spin states: destroys the magnetization and allows for more efficient optical pumping (less light detected by sensor)
- ν is frequency modulated: signal harmonics are demodulated and used to control a VCO to maintain optimum EPR (and pumping efficiency)



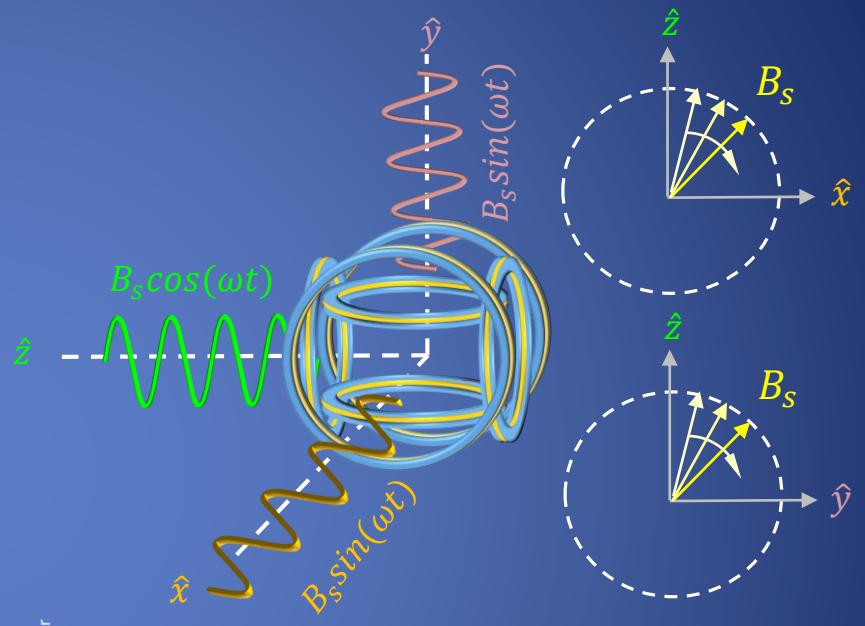


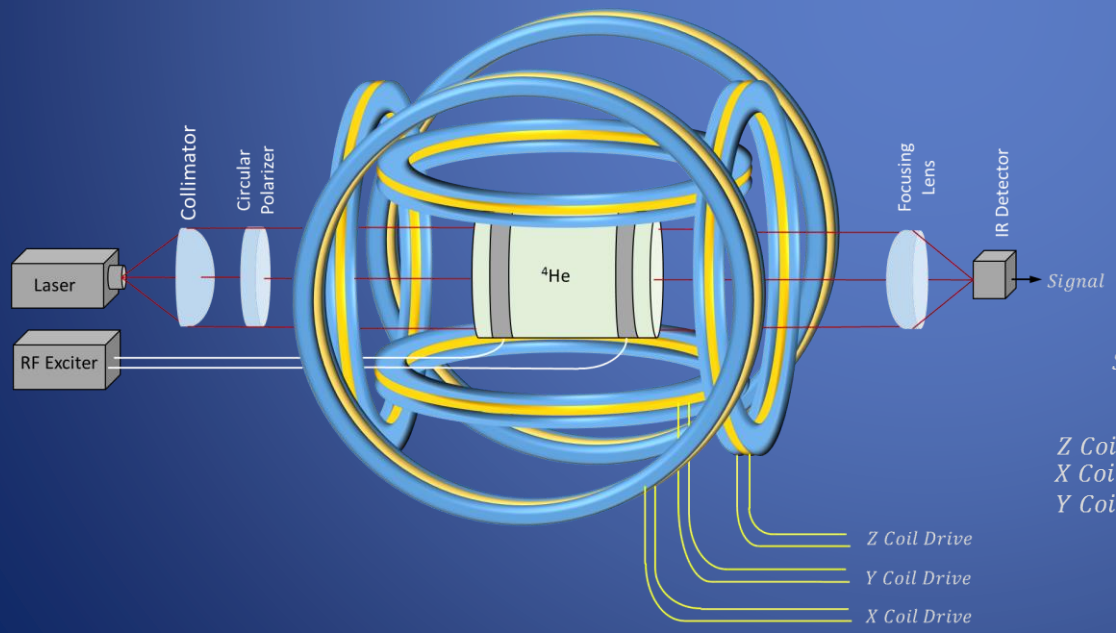


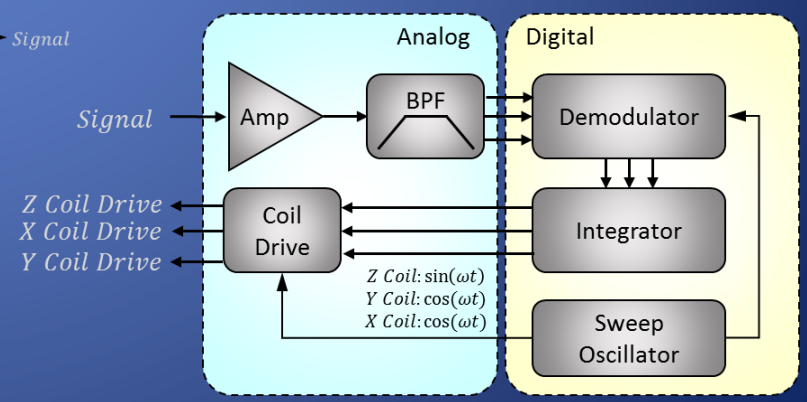


Vector Mode

- Magnetic field is measured by sensing changes in the absorption of optically pumped ^4He subjected to a rotating magnetic field in a plane containing the beam direction
- Optical pumping efficiency and absorption depends on angle between ambient field and optical axis
- The harmonics of the signal are demodulated and used to null the ambient field with the same coils used for the rotating field generation.







Outline

Part I

Brief Overview of JPL

Part II

Magnetometry

Part III

Magnetometers in Space

Part IV

Solid-state SiC based magnetometer

Introduction

- Fluxgates and optically pumped He gas magnetometers used on majority of missions
  - proven performance
  - reliability
  - ability to adhere to the levying constraints imposed on space flight missions

- Additionally, all of the planets and a few of their various moons have already been investigated.

- So why invest more time and research into creating new methods for magnetic field sensing?
  - Semiconductor technology is rapidly improving
    - Desire to miniaturize, simplify design, make purely electrical, and push the limits of sensitivity.
  - There will always be new missions ... may as well use updated technology
    - Magnetic fields are everywhere in space and influence many other phenomena (planetary dynamos, crustal fields, solar wind)
    - Don't have the complete picture, planetary fields change over time.

Motivation for New Technology

Highly sensitive magnetometers are too large for most cubesats (nano- and picosats)

MAVEN

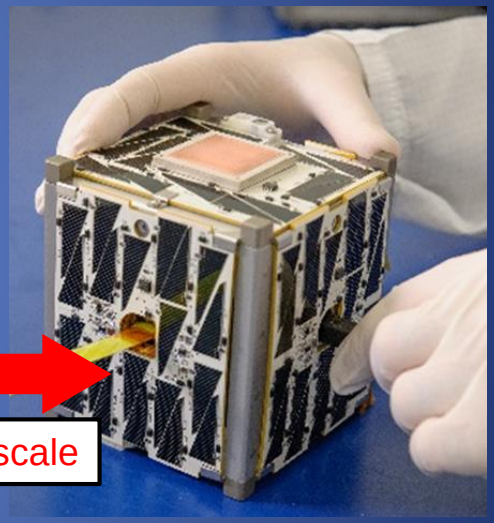
Fluxgate

Optically pumped

Pioneer 10/11

MAVEN

downscale



PhoneSat

For miniaturization, we need to look to the exponentially advancing semiconductor technology area!

Images credit: NASA

New Proposed Technology

- Detecting magnetic fields with a "defective" SiC microelectronic device
- Device: diode, BJT, MOSFET, dielectric
- Material: 4H crystalline Silicon Carbide with ion implanted Al and N donor atoms
- Based upon spin dependent recombination (SDR) or tunneling (SDT)

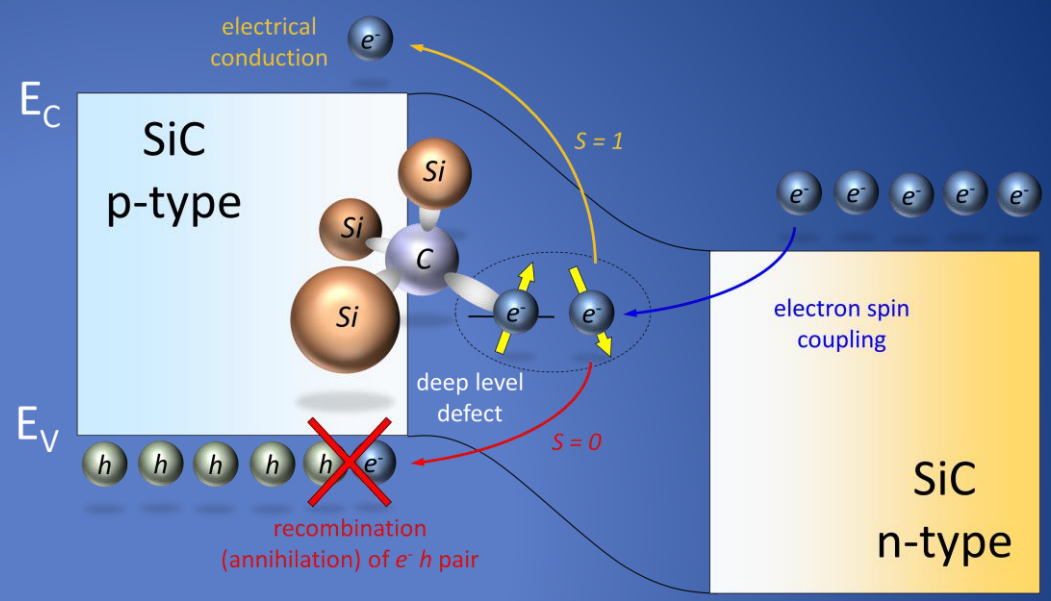
Sensor	Operation	Sensitivity $pT/\sqrt{Hz}$	Stability	Volume cm^3	Advantages	Disadvantages
Optically Pumped ^4He	Measures variations in optical pumping efficiency using EPR of excited He electrons	10's	<10pT	INSPIRE 500 (5x10x10)	• Very sensitive • Very stable • Absolute measurement • Scalar or vector modes	• Expensive • Complex • Requires optical and RF components which are temperature dependent • Requires resonant search • High power
Fluxgate	Saturation of ferromagnetic core, detection of offsets in induced voltage	10's	100's	MAVEN 936 (13x8x9)	• Inexpensive • Simple to implement • Robust • Moderately low power	• bulky • moderate stability
SiCMag	Changes in current from a SiC diode due to recombination dependence on external magnetic field	10's	100's	**0.008** (0.2x0.2x0.2)	• Inexpensive • purely electrical • extremely small • simple to implement • lightweight • very low power • high temperate operation • rad-hard sensor • Self calibrating	• risk in new technology

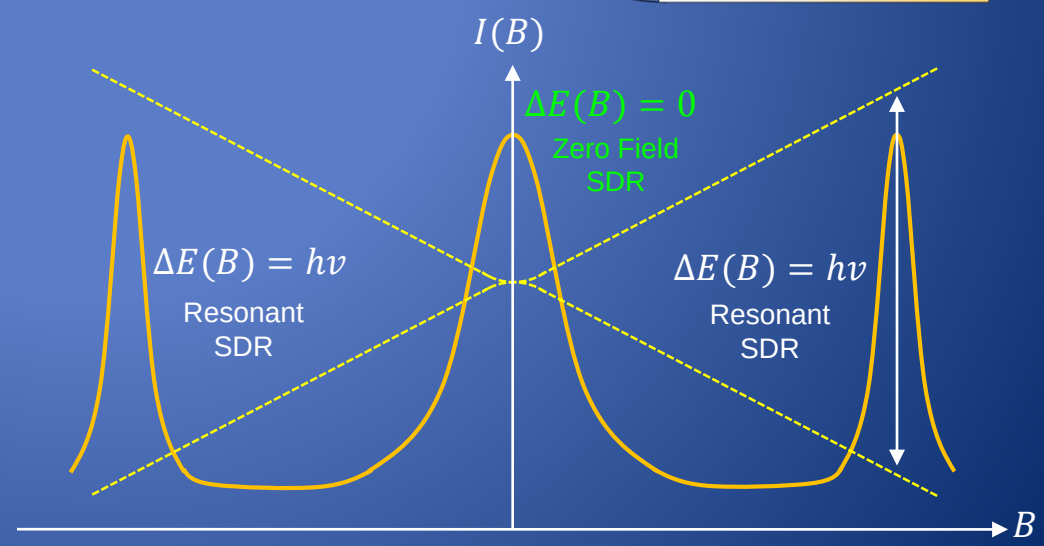
Advantages of Technology

- Solid state:
  - Purely electrical interface, digital output
- Simple:
  - Inexpensive, simplistic design, small footprint, low power
  - no high frequency RF or optical components which require stable temperatures (< 1kHz operation)
  - no "searching" for signal as in magnetic resonance based designs
  - No dead zones, simultaneous measurement of three axes using only a single sensor
- Can leverage heritage magnetometer components
  - Multi axis Helmholtz coils, FPGA, field cancellation routines, analog coil drive circuitry
- Magnetic field modulation:
  - Significantly reduces 1/f noise observed from DC current
  - Prevents DC sensor current drift
  - sharp zero-crossing (1st harmonic) or well defined peak (2nd harmonic) to lock onto
  - performed in software via computer, PIC microcontroller, or FPGA
  - Allows for vectorized magnetic field sensing
  - Modulation waveform can share the same set of Helmholtz coils as DC cancelling signal because audio frequencies used
  - Allows for detection of electron-nuclear hyperfine interactions
- 4H SiC diode sensor:
  - Single transistor used, uniform magnetic field through volume of device, potential for MEMS
  - Large bandgap (> 3eV): inherently rad hard and high temp environments (600 C, compared to 150 C for Si)
  - robust, no bias temperature instabilities as in organic semiconductors
  - Crystalline lattice allows for sharper signals to be detected, also unlike magnetoresistance in organic semiconductors
  - Ion implantation doping process naturally creates MANY defects in the SiC lattice, the more defects the better!
  - Magnet nature of dopant (B, Al, N, P) and host atoms (Si, C) allow it to be self-calibrating due to electron-nuclear hyperfine interactions

Detecting Magnetic Fields via Defects

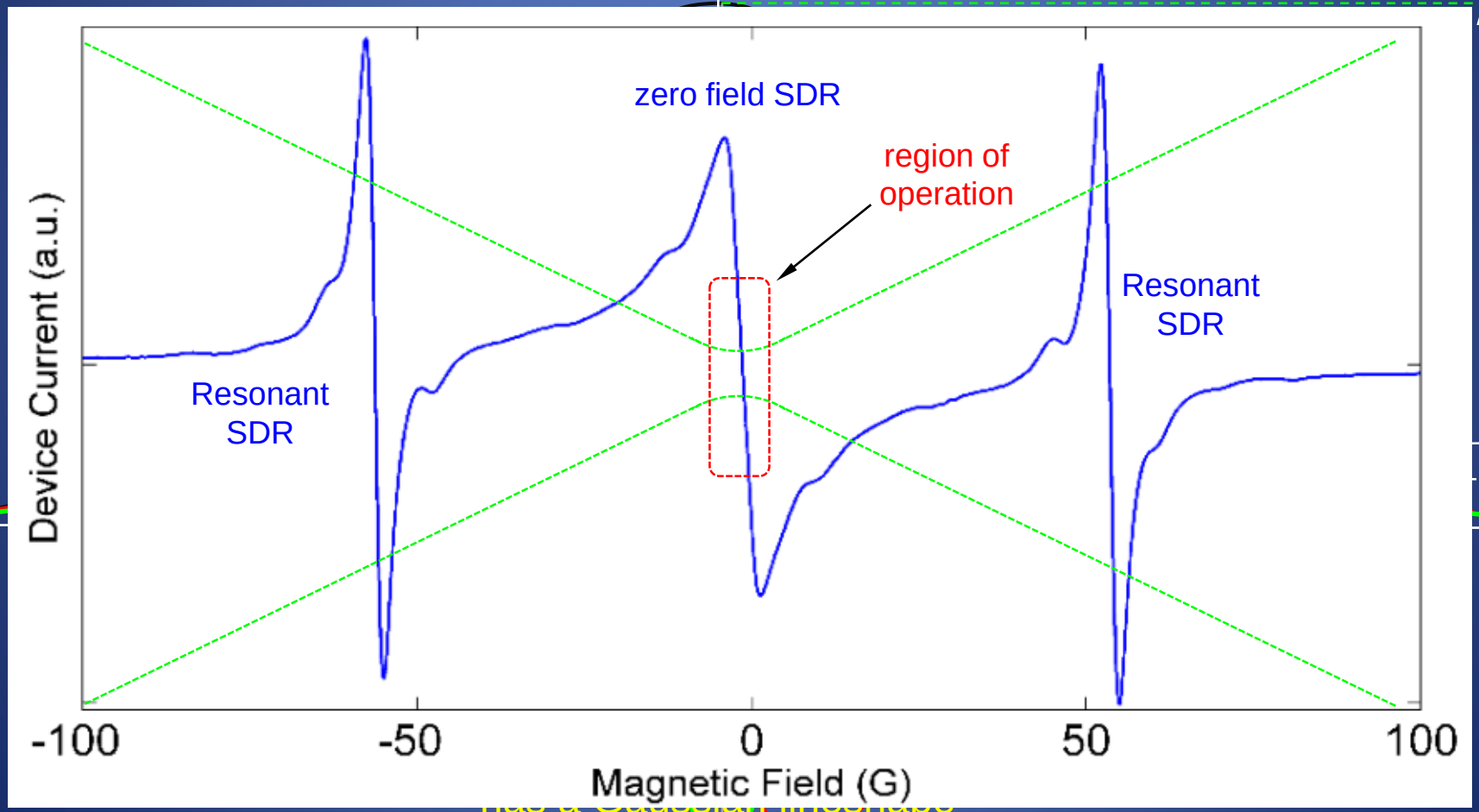
- Atomic scale defects have broken bonds that contain unpaired electronics which have intrinsic angular momentum called spin.
- Conduction electrons may couple with these defect spins which sometimes results in recombination with a hole if total angular momentum is conserved between the spin pair.
- In an applied magnetic field B, one can change the recombination rate by randomizing the spin-pair orientations, either by application of electromagnetic energy (resonant SDR) or turning off the external magnetic field (zero-field SDR).





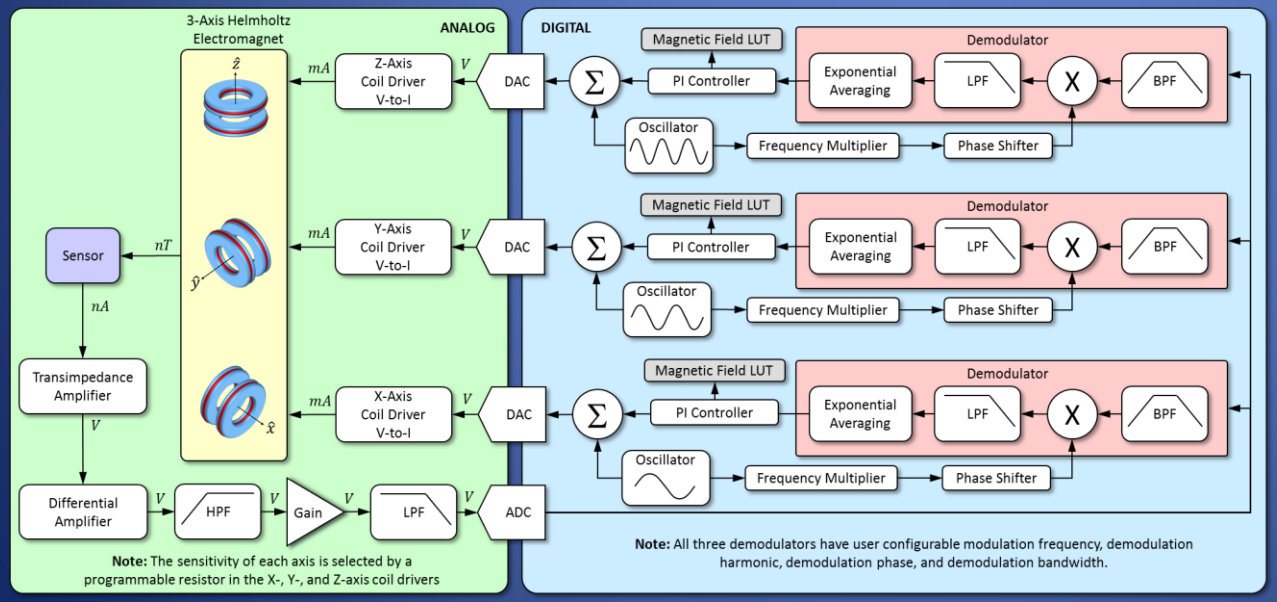
Magnetic Field Modulation

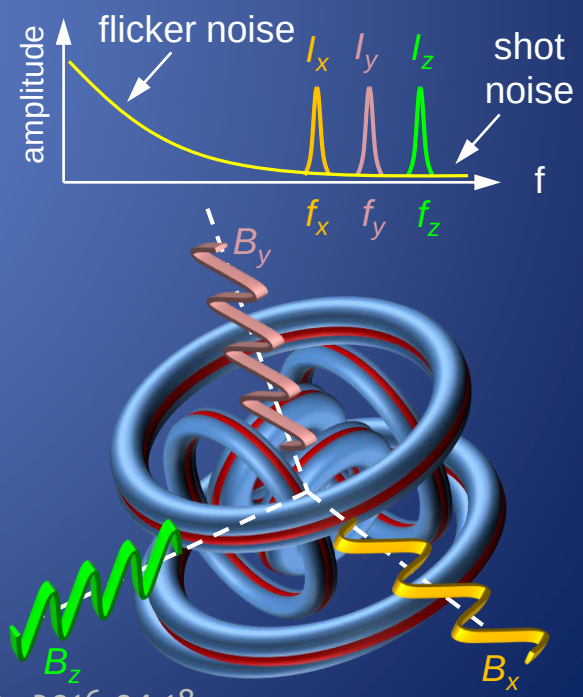
- Used to reduce noise, prevent drift, and allows for observation of a sharp zero crossing.
- Harmonics arise because of the spectral line shape.



Magnetometer Operation

- SiC diode is placed inside a network of Helmholtz coils, one set for each axis.
- Each coil modulates the external magnetic field (orthogonal audio waveforms) which frequency division multiplexes the components onto a single channel.
- The conditioned sensor current is digitized and fed through three independent software demodulators to extract the embedded current components
- A controller then tracks the zero crossing of these components and pumps each Helmholtz coil with the required current needed to maintain region of zero magnetic field across the sensor.

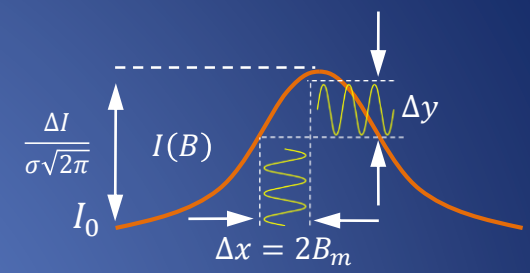




Sensitivity Analysis

$$Local\ Sensitivity:\ \delta y = \delta x \left|\frac{dy(x)}{dx}\right|_{x=0}$$

$\delta y = uncertainty\ in\ y \rightarrow \delta I_d$
$\delta x = uncertainty\ in\ x \rightarrow \delta B$



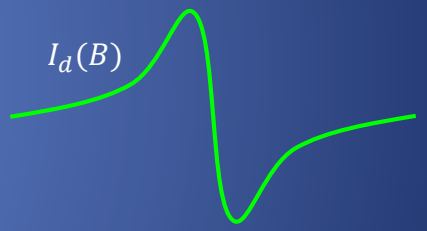
$$y(x) = measured\ data = I_d(B) = \Delta y = I(B + B_m) - I(B - B_m) = \frac{dI(B)}{dB}\Delta x \Big|_{\Delta x = B_m} \left(\frac{A}{T}\right)$$

$$I(B) = \frac{\Delta I}{\sigma\sqrt{2\pi}}\, exp\left\{-\frac{(B - B_r)^2}{2\sigma^2}\right\}\left(\frac{A}{T}\right)$$

$\Delta I = current\ change$
$\sigma = linewidth$

$$\delta I_d = \delta B \left|\frac{dI_d(B)}{dB} B_m\right|_{B=0} = {B_m}^2 \delta B \left|\frac{dI^2(B)}{dB^2}\right|_{B=0} = {B_m}^2 \delta B \frac{\Delta I}{\sigma^3\sqrt{2\pi}}\ (A)$$

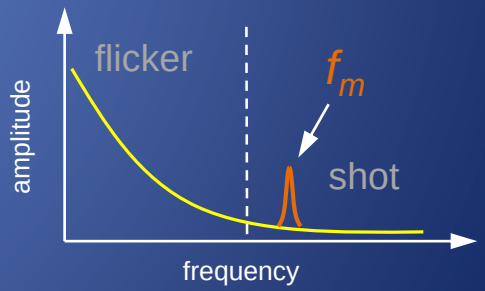
Because magnetic field modulation is utilized, flicker noise is avoided and shot noise determines the uncertainty in the measurement



$$\delta I_d = I_{shot} = \sqrt{2qI_0\Delta f}$$

$I_0 = DC\ current\ in\ the\ device$
$\Delta f = bandwidth\ of\ operation$

Putting everything together …



$$\delta B = \frac{\delta I_d\, \sigma^3\sqrt{2\pi}}{{B_m}^2 \Delta I} = \frac{\sqrt{2qI_0\Delta f}\,\sigma^3\sqrt{2\pi}}{{B_m}^2\Delta I} = 2\sqrt{\pi q}\frac{\sigma^3}{{B_m}^2}\frac{\sqrt{I_0}}{\Delta I}\sqrt{\Delta f}\ (T)$$

Modulating with $B_m = \sigma$, yields …

$$\delta B = 2\sigma\sqrt{\pi q}\frac{\sqrt{I_0}}{\Delta I}\sqrt{\Delta f}\ (T)$$

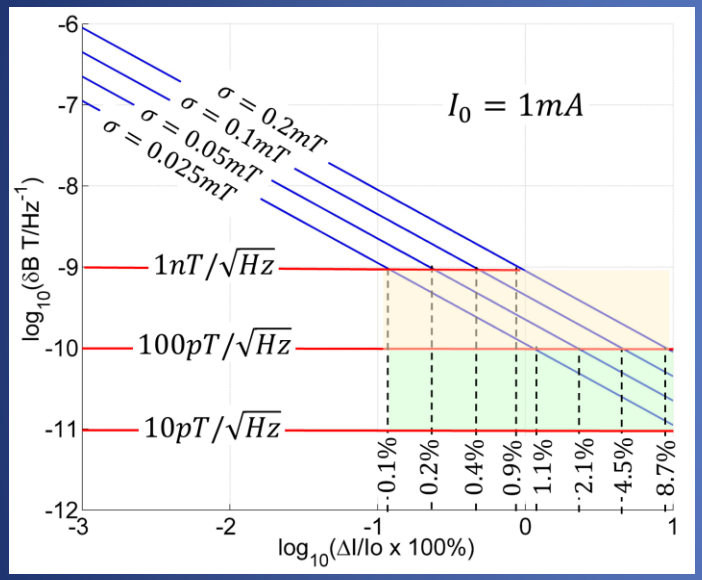
$$\frac{\delta B}{\sqrt{\Delta f}} = 2\sigma\sqrt{\pi q}\frac{\sqrt{I_0}}{\Delta I}\left(\frac{T}{\sqrt{Hz}}\right)$$

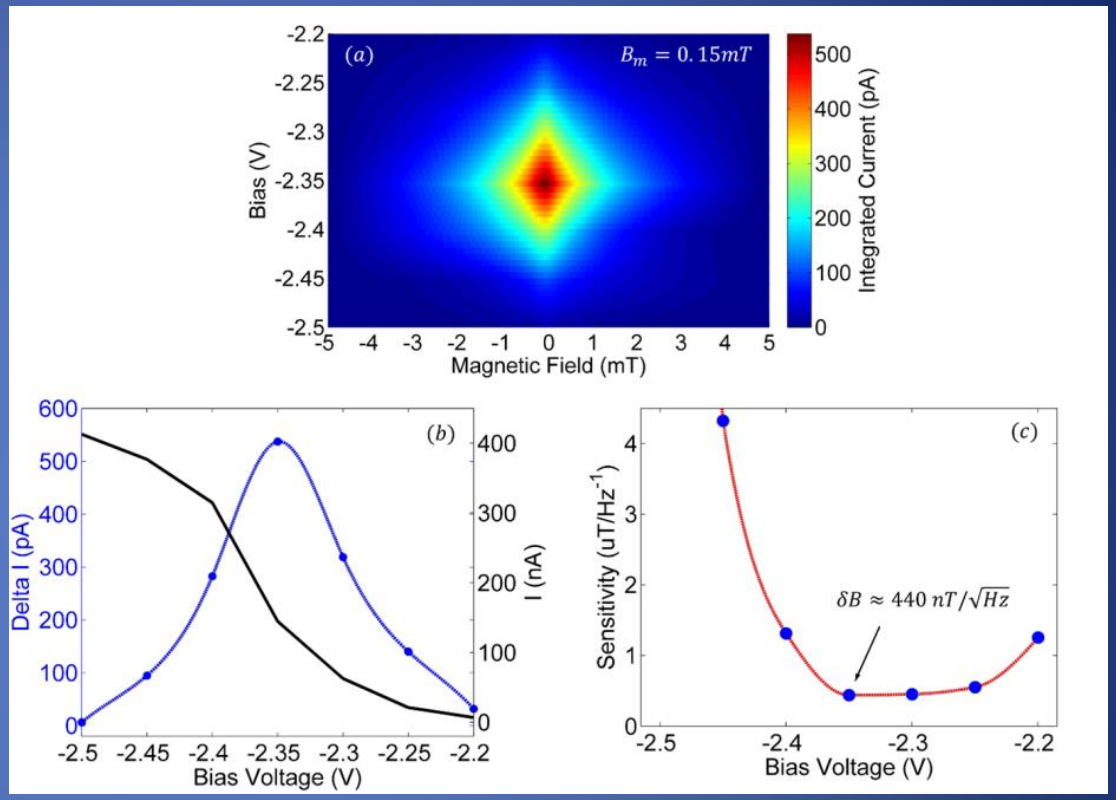
$\downarrow I_0 \quad \uparrow \Delta I \quad \downarrow \sigma$
$goal < 1nT$

Estimated Sensitivity

The theoretical sensitivity is

$$\frac{\delta B}{\sqrt{\Delta f}} = 2\sigma\sqrt{\pi q}\frac{\sqrt{I_0}}{\Delta I}\left(\frac{T}{\sqrt{Hz}}\right)$$





Measurements of the data set

$DC\ current\ I_0 = 145\ nA$

$change\ in\ current$: $\Delta I = 540\ pA$

$signal\ width$: $\sigma = 0.4\ mT$

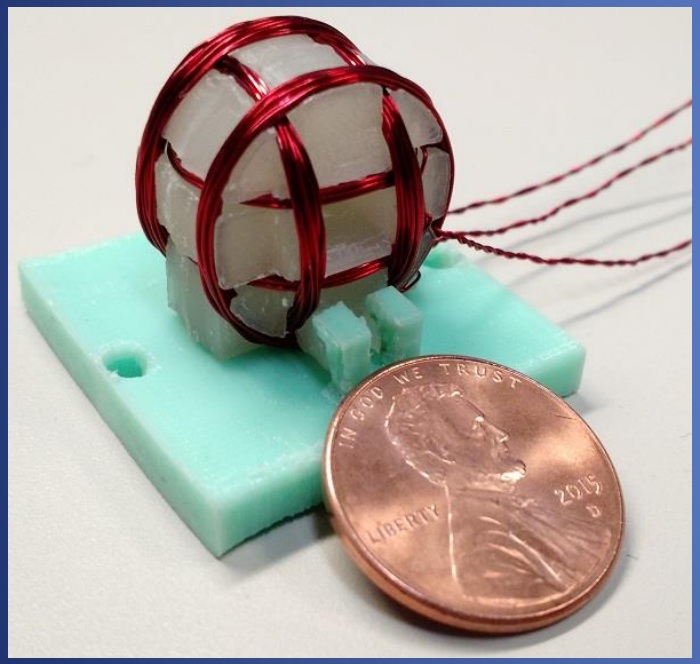
$$\frac{\delta B}{\sqrt{\Delta f}} = 440\frac{nT}{\sqrt{Hz}}$$

NOTES:

- Devices intended for power electronics and not magnetometry!
- Very easy to decrease I_0 and increase ΔI.
- Fluxgates and Helium magnetometers have more than 50 years of development.

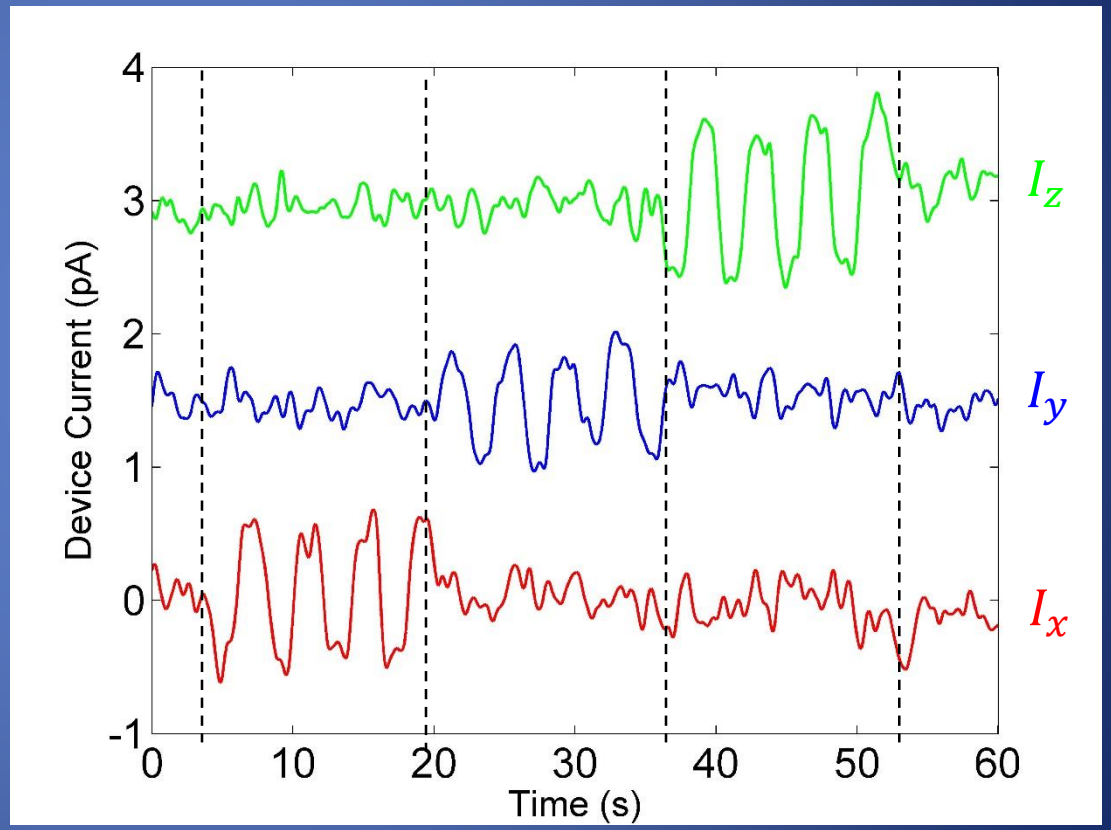
Vectorized Demonstration

3D Printed, 3-axis Helmholtz coil



Magnet fabrication: Gerardo Hernandez, JPL Summer Intern

+/- 1500 nT square wave applied to each axis



$$\frac{\delta B}{\sqrt{\Delta f}} = 440 \frac{nT}{\sqrt{Hz}}$$

Applications and Future Work

- Applications
  - planetary entry probes
  - Landers
  - missions in extreme environments
  - swarms of spacecraft significantly smaller than current nanosats

- Future Work:
  - Obtaining devices from NASA Glenn and possibly other companies
  - Determine processing specifications of best performing device
  - Work with group to optimize the geometry and processing.
  - Miniaturization of supporting components.

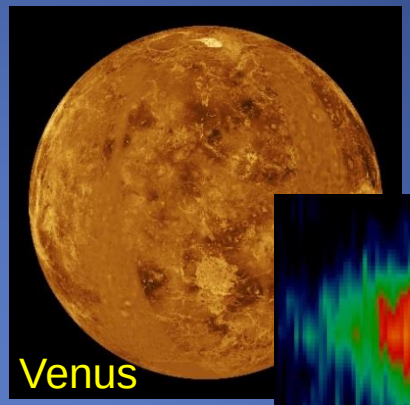
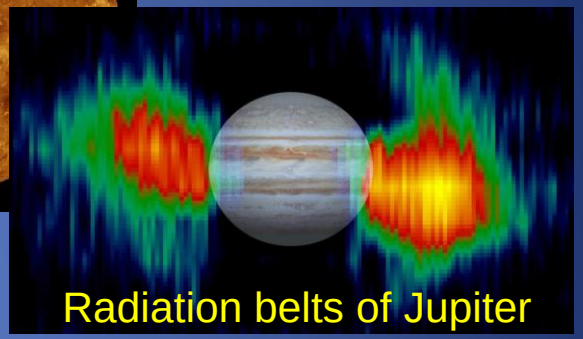
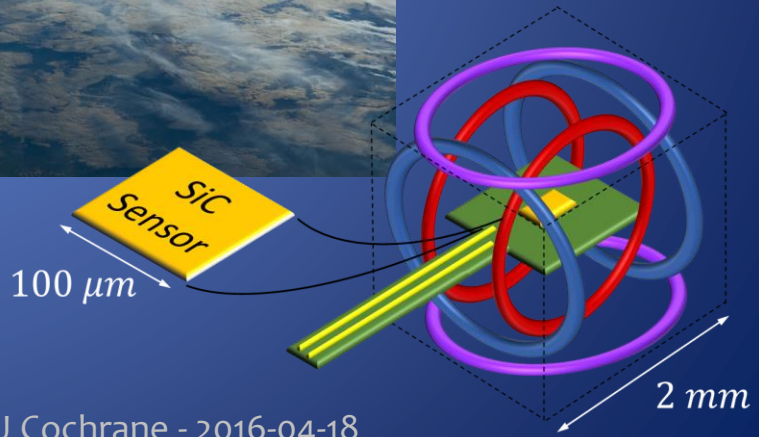


Image credit: NASA



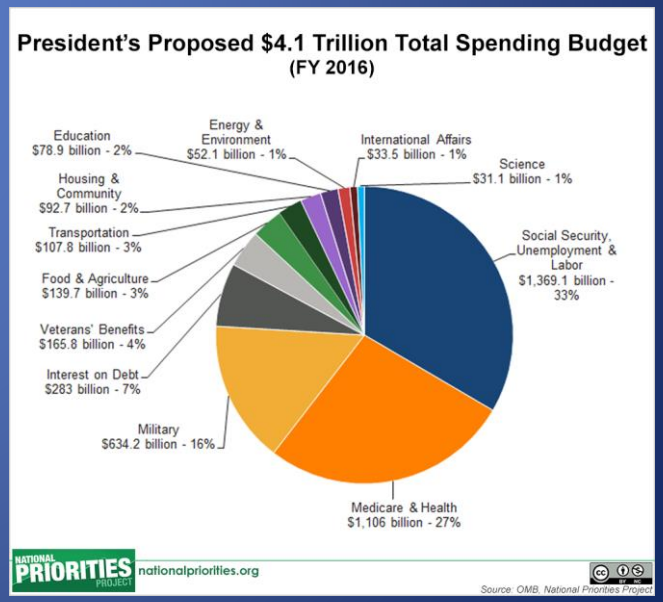
Miniaturization



Magnetometers Require the Effort of Many!

Multidiscipline Effort

1. Sensor
   - Device physics, fabrication, and reliability
2. Analog electronic circuit design
   - Amplification of tiny AC currents, low-noise/drift coil driving circuitry
3. Mechanical Design of Coils or MEMS
   - Coil fabrication, device integration with millimeter scale coils
4. Signal processing / Communication Systems
   - magnetic field modulation/demodulation, digital filtering, FPGA design
5. System engineering
   - Component integration, spacecraft integration
6. Data Analysis / Mathematical Modeling / Computer Science
   - Geomagnetism, plasma physics, solar system formation and evolution, feature identification
7. Business Sector
   - Finance, public outreach, administration, etc.



Global Effort

- NASA requires the support of the public as it is taxpayer funded
  - 2016: US Budget: $4 trillion, NASA budget: $18.5 billion, 320 million people contribute just a few dollars per month
- Missions require comm. and orbital planning across many countries
  - Launch windows, orbital paths, reentry, DSN, etc.
- The science return in not intended solely for NASA
  - There is a global interest in the origins of life and the solar system we live in.

Summary

- JPL has many years of experience developing magnetometers for space exploration, notable data obtained from Galileo and Cassini have been used to indirectly find water on Enceladus and Europa.
- Future and planned missions to Jupiter (Juno) and Europa will be equipped with a magnetometers to better understand this complicated system, the origins of our solar system, and determine the life harboring potential of the Jovian moon.
- These missions require multidisciplined teams and the collective effort of many countries.
- Being a part the scientific discovery driven engineering culture has helped myself think of ways to push the limits of magnetometer technology: maintaining sensitivity and stability while reducing size, cost, complexity and ability to be used in more extreme environments such as the surface of Venus.

Questions?

**"Scientists study the world as it is;
engineers create the world that has never been"**

-Theodore Von Karman, cofounder of JPL, on Engineering vs. Science