Io: A Casebook of Universal Plasma Processes

Fran Bagenal
University of Colorado
For example.........

<table>
<thead>
<tr>
<th>Io Story</th>
<th>Process</th>
<th>Universality</th>
</tr>
</thead>
</table>
| ![Auroral emissions](image-url) | e^- + N -> N^* + e^-  
N^* -> N + hν | ![Images of Io and Jupiter with auroras](image-url) |
OBSERVATIONS OF A VARIABLE RADIO SOURCE ASSOCIATED WITH THE PLANET JUPITER

BY B. F. BURKE AND K. L. FRANKLIN

Department of Terrestrial Magnetism, Carnegie Institution of Washington, Washington 15, D. C.

(Received April 15, 1955)

ABSTRACT

A source of variable 22.2-Mc/sec radiation has been detected with the large "Mills Cross" antenna of the Carnegie Institution of Washington. The source is present on nine records out of a possible 31 obtained during the first quarter of 1955. The appearance of the records of this source resembles that of terrestrial interference, but it lasts no longer than the time necessary for a celestial object to pass through the antenna pattern. The derived position in the sky corresponds to the position of Jupiter and exhibits the geocentric motion of Jupiter. There is no evident correlation between the times of appearance of this phenomenon and the rotational period of the planet Jupiter, or with the occurrence of solar activity. There is evidence that most of the radio energy is concentrated at frequencies lower than 38 Mc/sec.
~10s MeV electrons

B~few Gauss

~10° tilt of dipole
~10 hour rotation rate
<table>
<thead>
<tr>
<th>Jupiter Story</th>
<th>Process</th>
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<tbody>
<tr>
<td><img src="image1.png" alt="Jupiter Map" /></td>
<td>Radiation Belts</td>
<td><img src="image2.png" alt="Earth Diagram" /></td>
</tr>
<tr>
<td>Synchrotron Emission</td>
<td>Astrophysics: Pulsars Magnetars</td>
<td></td>
</tr>
</tbody>
</table>

Come to Next Heliophysics Summ
Jupiter Radio Emission
Discovered in 1955

- Jupiter has a magnetic field
- Trapped electrons
  \[ f_{\text{max}} \sim 40 \text{ Mhz} \]
  \[ f = f_c = qB/2\pi m \]
  \[ \rightarrow B_{\text{max}} \sim 14 \text{ G} \]
Early Discoveries

Io Phase

$\phi_{Io}$

B

A

Observer

Io’s Orbital Period = 42 hours

Jupiter’s Radio Emission Controlled by Location of Io

Bigg (1964)

Intensity

0° 90° 180° 270°

93° 138° 246°
Early Explanations

Goldreich & Lyndon-Bell (1969)

Conductor moving in magnetic field

Piddington & Drake (1968)

\[ E = -V \times B \]

\[ V = 57 \text{ km s}^{-1} \]

\[ \phi = 2 R_{\text{Io}} E = 400 \text{ kVolts} \]
Early Explanations

Radio emission beamed in a wide hollow cone on field line connected to Io by a current loop

*Dulk (1965)*
1979 Voyager flyby

- $\sim 3 \times 10^6$ Amp current
- $\delta B$, $\delta V$ consistent with Alfven wave
1979 Voyager flyby - The Io Alfvén Wave

\[ \frac{\delta B}{B} = - \frac{\delta V}{V_A} \]

\[ V_A = \frac{B}{(\mu_0 \rho)^{1/2}} \]
Looking From Side

\[ \theta \sim \frac{V_{\text{flow}}}{V_A} \sim 10^\circ \]

\[ V_{\text{flow}} \sim 57 \text{ km/s} \]

\[ V_A \sim 300 \text{ km/s} \]

Alfven wing / wave front / characteristic

Goertz 1980; Neubauer 1980
Southwood & Kivelson
Belcher 1987

Looking Upstream
Alfvénic Interaction

$T_{\text{Alfven}} > T_{\text{Transit}}$

DC Current Loop

$T_{\text{Alfven}} < T_{\text{Transit}}$
Momentum Coupling by Alfvén Wave

Motion of Io relative to plasma

- Slowing of ambient plasma
- Acceleration of Io Relative to Io orbital motion
- Slowing of ambient plasma

- $F \approx 5 \times 10^7$ N
- Thrust of a Saturn V booster
- Only moves Io few km outwards in age of solar system
Echo 1 sits fully inflated at a Navy hangar in Weeksville, North Carolina. The spacecraft measured 100 feet across when deployed, and was nicknamed a 'satelloon' by those involved in the project. Echo 1 was launched August 12, 1960, into an orbit with an Apogee of 1684 km, a Perigee of 1523 km and an Inclination of 47.2 degrees. The mylar film balloon acted as a passive communications reflector for transcontinental and intercontinental telephone (voice), radio and television signals. Echo 1 re-entered the atmosphere May 24, 1968.
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<td><img src="image1" alt="Io flux tube" /></td>
<td><strong>Momentum Coupling</strong></td>
<td>Anywhere the field is kinked or plucked</td>
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Examples of sorts of places this might happen?
Voyager Radio Discoveries

- Repeated patterns of arcs in frequency-time spectrographs
  - Indicates systematic beaming pattern, controlled by the geometry of Jupiter’s magnetic field
  - And location of Io…
Alfven Wave Theory

- Io generates Alfven waves
- Pattern of reflected waves carried downstream by corotating magnetospheric plasma
- Each Alfven wave excites an arc of radio emission.
- Nice idea—but predicted spacing is ~5 times too big
Multiple bounces between torus and Jupiter's ionosphere would explain close space of radio arcs.

This is what 1-D modeling of kinetic Alfvén waves is beginning to produce...

Crary & Bagenal 1997

Lysak et al. 2006
Model Equations

- Wave modeling based on Maxwell’s equations:
  \[
  \varepsilon \frac{\partial E_\perp}{\partial t} = \frac{1}{\mu_0} (\nabla \times B)_\perp - j_\perp \quad \frac{\partial B}{\partial t} = -\nabla \times E
  \]

- Current represents source due to Io, dielectric constant is:
  \[
  \varepsilon = \varepsilon_0 \left( 1 + \frac{c^2}{V_A^2} \right)
  \]

- where the Alfvén speed profile is given by the models above.

- These equations are cast in dipole coordinates, and the Green’s function for this system is found using Sturm-Liouville theory, assuming Io is essentially a point source.

- The Poynting flux delivered to the ionosphere can then be calculated as a function of frequency and the location of Io on the flux tube.
The Io Aurora

- energetic particles - electrons - bombard atmosphere
- ‘wake’ emission extends halfway around Jupiter
Power: $\sim 400 \text{ kVolts} \times 3 \text{ MAmps} \sim 10^{12} \text{ Watts}$
Galileo Io Flyby - 1995

Flow

Dense, Cold material

Fresh hot ions

Magnetic field

Electron Beams

Galileo
Amirani

300 km

Io
After quantities of lava are removed from below, the crust cracks and tilts, making tall, blocky mountains.
Io’s Volcanoes & Geysers

Prometheus

Pilan 5 months apart

Pilan Plume

Infrared

Pele
New Horizons

Io’s Nightside

Tvashtar

MVIC

LORRI

IR LEISA
Io Plume Movie

- 5 frames
- 2 mins between frames
- Ballistic trajectories with fallout time of ~30 mins
1998 observations

Because SO$_2$ gas absorbs strongly at 1215Å, Lyman-α images provide a map of the SO$_2$ atmosphere on Io. Dark=more SO$_2$ gas.

Lyman-α Images $\rightarrow$ $N_{SO_2} \sim \text{few x } 10^{16} \text{ cm}^{-2}$

Note the pronounced variability in the inferred abundance and distribution of the gas between 1998 & 1999. It is unclear at present whether this variability is temporal or longitudinal.

Io campaign observations, 1999
Galileo - Nightside of Io - Visible

Glowing Lava

Plume Gas & Dust + Aurora
io-plasma interaction: HST data vs. model

Hubble Space Telescope image of O+ emission - Roessler et al. 1997

MHD model of Io interaction - prediction of O+ emission excited by electron impact - Linker & McGrath 1998
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<tr>
<td>[Image]</td>
<td>Auroral emissions &lt;br&gt; $e^- + N$ &lt;br&gt; $\rightarrow N^+ + e^-$ &lt;br&gt; $N^+ \rightarrow N + h\nu$</td>
<td>[Images]</td>
</tr>
</tbody>
</table>
Local hot pick-up source:
3-20 x 10^{27} s^{-1}
<100 kg s^{-1}

“cold slug”:
3-20 x 10^{26} s^{-1}
~ 10-70 kg s^{-1}

Total ion source 200-1200 kg s^{-1} - Mostly far from Io
Total mass \( \sim 2 \) Mton
Source @ \( \sim 1 \) ton/s
\( \sim 3 \times 10^{28} \) ions/s
replaced in 23 days
Io Plasma torus:
Total mass ~ 2 Mton
Source @ 1 ton/s replaced in 23 days

Total thermal energy ~6 x 10^{17} J
UV power @ 1.5 terawatt cools electrons in ~7 hours
Ion pick-up @ 2 terawatt generates total energy in 4 days
QuickTime™ and a YUV420 codec decompressor are needed to see this picture.
How do composition, temperatures & UV power vary?

Cassini UVIS

Andrew Steffl, PhD 2005

UVIS FUV Spectrum of the Io plasma torus
Torus Chemistry Models

Neutral Cloud Theory:
Source = atomic O, S
Ionization, Charge Exchange, Recombination
Radiative Cooling
Ion-Electron coupling - Coulomb collisions

Electron heating:
Necessary to provide UV emitted power
Usually specified as $F_{\text{hot}} = \frac{N_{e_{\text{hot}}}}{N_{e_{\text{cold}}}}$ and $T_{\text{hot}}$

Homogeneous Volume
Five Parameters:
Transport Timescale - $\tau_{\text{transport}}$
Source of Neutrals - $S_{\text{neutrals}}$
Oxygen to Sulfur Ratio - $\frac{O}{S_{\text{neutrals}}}$
Hot Electron Fraction - $F_{\text{hot}} = \frac{N_{e_{\text{hot}}}}{N_{e_{\text{cold}}}}$
Hot Electron Temperature - $T_{\text{hot}}$

Output:
Neutral, Ion, Electron Densities
Ion Temperatures
Thermal Electron temperatures
Mass, Energy Flows
**Pick-up Energy**

\[ \mathcal{E} = \frac{1}{2} m_{\text{ion}} V^2 \]

**Pick-up Current**

\[ J_{pu} = N e 2r_g^+ \]

---

*Extracting momentum from the flowing plasma
Converting bulk motion into gyromotion*
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<td></td>
<td>Ion Pick-Up</td>
<td>Solar wind + Interstellar pick-ions</td>
</tr>
</tbody>
</table>

Diagram:
- E
- $2r_g$
- $\otimes B$
- $j_{pu}$
- Comets
<table>
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<tr>
<th>Reaction</th>
<th>$k$, cm$^3$s$^{-1}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$S^+ + S^{++} \rightarrow S^{++} + S^+$</td>
<td>$k_0 = 8.1 \times 10^{-9}$ — Smith &amp; Strobel 1985</td>
</tr>
<tr>
<td>$S + S^+ \rightarrow S^+ + S$</td>
<td>$k_1 = 2.4 \times 10^{-8}$</td>
</tr>
<tr>
<td>$S + S^{++} \rightarrow S^+ + S^+$</td>
<td>$k_2 = 3 \times 10^{-10}$</td>
</tr>
<tr>
<td>$S + S^{++} \rightarrow S^{++} + S$</td>
<td>$k_3 = 7.8 \times 10^{-9}$</td>
</tr>
<tr>
<td>$S + S^{+++} \rightarrow S^+ + S^{++}$</td>
<td>$k_4 = 1.32 \times 10^{-8}$</td>
</tr>
<tr>
<td>$O + O^+ \rightarrow O^+ + O$</td>
<td>$k_5 = 1.32 \times 10^{-8}$</td>
</tr>
<tr>
<td>$O + O^{++} \rightarrow O^+ + O^+$</td>
<td>$k_6 = 5.2 \times 10^{-10}$</td>
</tr>
<tr>
<td>$O + O^{++} \rightarrow O^{++} + O$</td>
<td>$k_7 = 5.4 \times 10^{-9}$</td>
</tr>
<tr>
<td>$O + S^+ \rightarrow O^+ + S$</td>
<td>$k_8 = 6 \times 10^{-11}$ — McGrath &amp; Johnson 1989</td>
</tr>
<tr>
<td>$S + O^+ \rightarrow S^+ + O$</td>
<td>$k_9 = 3.1 \times 10^{-9}$</td>
</tr>
<tr>
<td>$S + O^{++} \rightarrow S^+ + O^+$</td>
<td>$k_{10} = 2.34 \times 10^{-8}$</td>
</tr>
<tr>
<td>$S + O^{+++} \rightarrow S^{++} + O^+ + e^-$</td>
<td>$k_{11} = 1.62 \times 10^{-8}$</td>
</tr>
<tr>
<td>$O + S^{++} \rightarrow O^+ + S^+$</td>
<td>$k_{12} = 2.3 \times 10^{-9}$</td>
</tr>
<tr>
<td>$O^{++} + S^+ \rightarrow O^+ + S^{++}$</td>
<td>$k_{13} = 1.4 \times 10^{-9}$</td>
</tr>
<tr>
<td>$O + S^{+++} \rightarrow O^+ + S^{++}$</td>
<td>$k_{14} = 1.92 \times 10^{-8}$</td>
</tr>
<tr>
<td>$O^{++} + S^{++} \rightarrow O^+ + S^{+++}$</td>
<td>$k_{15} = 9 \times 10^{-10}$</td>
</tr>
<tr>
<td>$S^{+++} + S^+ \rightarrow S^{++} + S^{++}$</td>
<td>$k_{16} = 3.6 \times 10^{-10}$</td>
</tr>
</tbody>
</table>
Particle Flow
Total = 10 \times 10^{-4} \text{ cm}^{-3} \text{ s}^{-1}

S 20% S, S^+, S^{++}, S^{+++} 
O 80% e^- e^-, O, O^+, O^{++}

hot e-
fast neutrals

transport 67% 33%
Energy Flow
Total = 0.41 \text{(eV cm}^{-3}\text{ s}^{-1})

80% energy from pick up

20% energy from hot electrons

70% energy radiated in UV
1. Pickup in Io torus (500 eV)
2. Cold neutral wind
Na = good tracer - we expect S & O to do similar

1000 Rj ~ 0.5 AU!
1. keV-MeV particles charged-exchanged with neutrals
2. Energetic neutral escapes - ENA
3. Re-ionized (ChEx with SW protons)
4. MEV S⁺ picked up in solar wind
Energetic Neutral Atoms - produced by charge exchange
Cassini Energetic Ions - 55-220 keV
Upstream of Jupiter
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<tr>
<td></td>
<td>Charge Exchange</td>
<td>Solar wind + Interstellar pick-ions</td>
</tr>
<tr>
<td></td>
<td>$X^+ + Y \rightarrow Y^{++} X_{fast}$</td>
<td>Earth Plasmasphere</td>
</tr>
</tbody>
</table>
**Io Plasma Torus**

- $5 \times 10^{34}$ ions O$^+$, S$^{++}$
- $N_{\text{neutral}} \sim 50$-100 cm$^{-3}$
- $N_{\text{ions}} \sim 2000$ cm$^{-3}$
- Pick-up energy
  - $1.5$-$2 \times 10^{12}$ W
- UV power $\sim 3 \times 10^{12}$ W

**Enceladus Neutral Torus**

- $4 \times 10^{34}$ O atoms
- $N_{\text{neutral}} \sim 750$ cm$^{-3}$
- $N_{\text{ions}} \sim 100$ cm$^{-3}$
- Pick-up energy
  - $1.4 \times 10^{10}$ W
So, what's going on electrodynamically near Io?

Flow around a perfectly conducting sphere - or cylinder

X 2 flow speed on sides
Does Io Have a Magnetic Dynamo?

- Magnetic field geometries look very similar
- To distinguish between the two models we need to fly over the pole
- Answer? Probably NO.

MHD model Linker et al. 1996
Ionospheres - Sets boundary conditions for magnetospheric dynamics
Electrical Conductivity in Plasmas

(a) Collisional Case

\[ K = \text{gyrofrequency} \]

\[ \kappa_e, \kappa_i \ll 1 \]

(b) Collisionless Case

\[ \kappa_e, \kappa_i \gg 1 \]

(c) Intermediate Case

\[ \kappa_i = 1 \]
Earth's Ionospheric Conductivity

In reality:
- Anisotropic
- Varies with time
- Spatially variable
- Changes with input from magnetosphere

Common models:
- Simple slab of net conductance

\[ \Sigma_P = \int \sigma_P \quad \Sigma_P = \int \sigma_H \]
**Io Plasma-Atmosphere electrodynamics**

- Electrodynamics: Induction and Pick-up currents deflect flow
- Heating, ionization and charge-exchange in atmosphere
- Cooling, deceleration of upstream plasma
- Acceleration of downstream plasma
- Messy!

*Saur et al. 2002*

*Delamere et al. 2003*
Hybrid Model: Fluid electrons, kinetic ions

Density

Velocity

Delamere
Momentum Coupling by Alfvén Wave

Motion of Io relative to plasma

Slowing of ambient plasma

Acceleration of Io Relative to Io orbital motion

Slowing of ambient plasma

Pick-Up currents act same way as conduction currents in Io
Couple momentum between "object" and surrounding plasma
MHD/electrodynamic

Hybrid (fluid electrons, particle ions)

Hybrid / Kinetic

Io

Comet Borrelly

Pluto
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<td></td>
<td>Momentum Coupling</td>
<td>Anywhere the field is kinked or plucked - DUE TO MASS LOADING</td>
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</table>

- Cold, Dense Ionospheric Plasma

![Diagram of Io and the solar wind](image)

- Momentum Coupling

![Diagram of momentum coupling](image)

- Universality Process Io Story

![Diagram of Io in the solar system](image)
3 Phases of the Io Interaction

(1) Io interaction

(2) Coupling to the torus

(3) Coupling to the ionosphere
What happens between the torus and Jupiter where the density is very low?

Phase II: Pick-up of New Plasma in Io’s Wake

- Coupling to torus plasma
- Alfven travel-time to “edge” of torus
- Acceleration to few% of corotation
- 2-D MHD in non-uniform background plasma

Delamere et al. 2003
Main L-Bursts

Ergun et al 2006

Long bursts - Radio emissions

Just like Earth!

Earth During Substorm

Alfvén Waves

“S-Bursts”

AKR

Reconnection Region

Plasma Sheet

Near steady-state current systems.

Short bursts

Just like Earth!
Based on Earth Experience:

- 3 current types
- Alfven: alternating
- Upward: e\(^-\) -> atmosphere
- Downward: moves upwards, transient
Alfven Resonator

- Accelerates outward electron beams
-> Short-Bursts of radio emission

Launch a wavepacket

Kinetic Alfven wave in dipole field with Prescribed $V_A$ profile

Su et al. 2006
QuickTime™ and a YUV420 codec decompressor are needed to see this picture.
QuickTime™ and a YUV420 codec decompressor are needed to see this picture.
Unstable electron distribution function

-> Cyclotron Maser Instability

-> EM radiation at $F_{ce}$

Beamed in hollow cone
Kinetic Code: Calculate change in particle distribution function due to wave fields

\[ F = (\nabla \times \mathbf{b}) \times \mathbf{b} \]
Short Radio Emissions

aka S-Bursts

frequency ~ 20 Mhz
Duration ~ 10s milliseconds
Drift ~ 10 MHz/s
e- moving $10^4$-$10^5$ km/s
Several keV
Lowering f -> away from Jupiter

e.g. Hess et al. 2007
What about the wake?
Steady-state Boundary conditions set ionosphere torus
10s kV Potential drops

Su et al. 2003
Vlasov Code: Calculate steady-state particle distribution function due to imposed gravitational, centrifugal and electrostatic potentials
3 Phases of the Io Interaction

(1) Io interaction

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<tr>
<td>[Image of Io Story]</td>
<td>[Diagram of Process]</td>
<td>ALL magnetosphere?</td>
</tr>
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</table>

**Io Story**
- Io Story

**Process**

**Downward Current Region**
1. Downward current. \( \uparrow \downarrow J \)
2. Diverging electric field structures.
3. Small-scale density cavities.
4. Up-going, field-aligned electrons. \( \uparrow \downarrow e^- \)
5. Ion heating transverse to \( B \). Energetic ion conics.
6. ELF electric field turbulence.
7. 3-D Electron solitary waves.
8. VLF saucer source region.

**Upward Current Region**
1. Upward current. \( \uparrow \downarrow J \)
2. Converging electric field structures.
3. Large-scale density cavities.
4. Down-going, inverted-V') electrons. \( \downarrow \uparrow e^- \)
5. Up-going ion beam. Ion conics.
6. Large-amplitude ion cyclotron waves and electric field turbulence.
8. AKR source region.

**Alfven Current**
1. Variable Currents. \( \uparrow \downarrow J \)
2. Alfvénic electric fields.
3. No density cavity.
4. Counter-streaming electrons. \( \uparrow \downarrow e^- \)
5. Ion heating transverse to \( B \). Intense ion outflow.
6. ELF electric field turbulence. Ion cyclotron waves.
7. 3-D Electron solitary waves.
Juno
Jupiter
Polar
Orbiter
Juno arrives at Jupiter in 2016.
Other Plasma-Atmosphere Interactions
Venus, Mars, Titan - Ionospheres + Bow Shocks
- Ancient dynamo
  - early protection for atmosphere
- Strong crustal magnetization
  - affect atmospheric loss after dynamo turn-off
Magnetization only of old, cratered terrain

=> Dynamo ceased ~3.5 billion years ago
Wow! It's hot!

Heat Flux $\sim 10^{10}$ W

Water vapor escaping - but is there a substantial reservoir of liquid water?
CU’s UltraViolet Imaging Spectrometer on Cassini
Atmospheres

McGrath et al. 2004

- $\text{SO}_2, \text{S}_2$
- $1-10 \times 10^{16} \text{ cm}^{-2}$
- $\times 10^? \text{ over plumes}$

- $\text{H}_2\text{O}$
- $1.5 \times 10^{16} \text{ cm}^{-2}$

Area of Io = $(3630/500)^2 = 53 \text{ times Enceladus}$

UVIS
## Atmospheric Loss

<table>
<thead>
<tr>
<th></th>
<th>Mol/atom loss</th>
<th>Molecular loss</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mol/atom loss</td>
<td>$3 \times 10^{28} \text{ s}^{-1}$</td>
<td>$5 \times 10^{27} \text{ s}^{-1}$</td>
</tr>
<tr>
<td>Mass loss</td>
<td>3000 kg s$^{-1}$</td>
<td>150 kg s$^{-1}$</td>
</tr>
<tr>
<td>Ionization</td>
<td>1000 kg s$^{-1}$</td>
<td>10 kg s$^{-1}$</td>
</tr>
<tr>
<td>Io Plasma Torus</td>
<td>Enceladus Neutral Torus</td>
<td></td>
</tr>
<tr>
<td>----------------</td>
<td>------------------------</td>
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<tr>
<td>1.5-2 x $10^{12}$ W</td>
<td>1.4 x $10^{10}$ W</td>
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<tr>
<td>UV power $\sim 3 \times 10^{12}$ W</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
$\Delta B/B = 0.45$

$I = 3 \text{ MA}$

900 nT
$\Delta B = 20 \text{ nT}$

$\Delta B/B = 0.07$