Aurora and hard disc drives: Using physics to play at large and small scales

M. T. Johnson
University of MN – Duluth
October 24, 2013
Outline

• Some background about me.
• **Space Physics:** Where do the Aurora come from?
  • Space plasmas, the magnetosphere.
  • The Lightning Bolt rocket mission.
  • Plasma Density Measurements using the Polar Spacecraft.
• **Hard disc drives:** High tech on small scales (~ 1nm).
  • Where I work now.
  • Basics of the technology.
  • Wow! These things are really “Nanotechnology!”
Some background about me

• Grew up in Southern Minnesota (Winnebago)
• Ph. D. Physics, U of MN, TC - 2002.
  • Langmuir probe on the “Lightning Bolt” Sounding rocket mission.
  • Analysis of the plasma density in the Magnetosphere using the Electric field instrument on the Polar satellite.
• Mechanical Research and Development at Seagate’s Recording Head Operations in Bloomington, MN. - 2003 to present
  • Development of fundamental understanding of thermal-mechanical systems and wear mechanisms on a nano-scale.
Space physics: Measuring Plasma Densities

What causes the Aurora Borealis?
Physics between the Earth and the moon…
Space Physics – Where do the Aurora come from?

Auroral Oval over the Northern Hemisphere using the UVI experiment on the Polar spacecraft. Viewed from 8 RE (~51,000 km or 31,000 mi) altitude [Parks, 1996]

Aurora over Spicer, MN [Randall Wehler, August 1991]

Aurora seen from the space shuttle at ~600 km (370 mi) [NASA picture library]
Space plasmas: Space is not empty!

The large scale features of the **magnetosphere** in the noon-midnight plane [Parks, 1991].

<table>
<thead>
<tr>
<th>Plasma Type</th>
<th>Density ($m^{-3}$)</th>
<th>Temperature (eV)</th>
<th>Debye Length (m)</th>
<th>$N_0$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Interstellar</td>
<td>$10^0$</td>
<td>$10^{-1}$</td>
<td></td>
<td>$10^{10}$</td>
</tr>
<tr>
<td>Solar wind</td>
<td>$10^2$</td>
<td>10</td>
<td>1</td>
<td>$10^9$</td>
</tr>
<tr>
<td>Solar corona</td>
<td>$10^{12}$</td>
<td>$10^2$</td>
<td>$10^{-3}$</td>
<td>$10^{13}$</td>
</tr>
<tr>
<td>Solar atmosphere</td>
<td>$10^{20}$</td>
<td>1</td>
<td>$10^{-6}$</td>
<td>$10^2$</td>
</tr>
<tr>
<td>Magnetosphere</td>
<td>$10^7$</td>
<td>$10^2$</td>
<td>$10^{-2}$</td>
<td>$10^{13}$</td>
</tr>
<tr>
<td>Ionosphere</td>
<td>$10^{12}$</td>
<td>$10^{-1}$</td>
<td>$10^{-3}$</td>
<td>$10^4$</td>
</tr>
<tr>
<td>Gas discharge</td>
<td>$10^{20}$</td>
<td>1</td>
<td>$10^{-6}$</td>
<td>$10^2$</td>
</tr>
<tr>
<td>Fusion machine</td>
<td>$10^{22}$</td>
<td>$10^5$</td>
<td>$10^{-5}$</td>
<td>$10^7$</td>
</tr>
</tbody>
</table>

Plasmas in space near the earth can range from <0.01 to over 10e5 cm$^{-2}$! Properties of typical plasmas [Kivelson and Russel, 1995]
Space plasmas: The Lightning Bolt Rocket Mission

• The “Lightning Bolt” Rocket mission was launched to study the propagation of electromagnetic waves (generated by lightning) through the ionosphere.
• How do the waves evolve as they propagate into/through the plasma of the ionosphere?
• The rocket was launched over the Atlantic ocean from NASA Wallops Flight Center, MA.
• I worked on the Langmuir probe instrument which measures plasma densities and temperatures.

The Lightning Bolt Sounding Rocket on the launch rail.
Space Plasmas: The Lightning Bolt Rocket Mission

(Above) The rocket was launched at night because of the ambient light requirements for the photo detector.

(Right) The rocket ready for launch.

The payload included several instruments.

In particular: Two sets of magnetometers, an electric field instrument, a photodetector, and a Langmuir probe.
Polar Spacecraft: Measuring plasma densities

The Polar spacecraft has 13 instruments to used to study mechanisms that are responsible for the aurora [Harten and Clark, 1995].

(Above) Plot of the magnitude of the electron plasma flux to the Hydra detector as a function of energy and time. Color indicates magnitude of the flux. The black line shows spacecraft potential measured using the Electric Field Instrument (EFI) [Scudder, 2000].

Diagram of the balance of electron currents to and from the satellite. The potential of the satellite is set by the balance of photoelectric and thermal electron currents.

The Polar spacecraft has 13 instruments to used to study mechanisms that are responsible for the aurora [Harten and Clark, 1995].
Polar Spacecraft: Plasma density maps

(Above) Plasma density over the polar cap at 1Re [6400 km] altitude depends on the illumination of the ionosphere [Johnson, 2001]

(Right) Density of plasma in the ionosphere [Hargreaves, 2002]

(Top) The large scale features of the magnetosphere in the noon-midnight plane [Parks, 1991].
(Bottom) Spatial distribution of the plasma in the magnetosphere generated using 6 years of Polar spacecraft potential data [Johnson, 2002]
The Nanotechnology of Hard Disc Drives

Now for small things…
Seagate Recording Heads Division

The Recording Heads operation is Seagate’s internal and principal supplier of recording heads. The division’s leading research and development capabilities continually push the technology envelope – allowing the company to design and develop industry-leading advanced read/write heads for disc drives.

Head technology is the most precise, complex and dynamic technology in the computing industry; heads are no larger than a grain of coarse sand. Everyone who operates a computer relies upon this technology, as it is the head that writes, saves, erases, sends and receives data. More than 1,950 employees reside at this Seagate location.
Packing in the data

1984

Wren
Five 5¼” Discs
86 Mbytes
61 floppy discs

FMD
Twelve 14” Discs
675 Mbytes
> 100 lbs.

1991

Wren
Five 5¼” Discs
330 Mbytes

Sabre
Eleven 8” Discs
3 Gbytes
28 lbs.

1996

Elite
Fourteen 5¼” Discs
23 Gbytes

2000

Cheetah
Twelve 3” Discs
73 Gbytes

2010

FreeAgent®
GoFlex™
3 Tb
USB3
2.38 lb

2007

ST1
One 1” Disc
8 Gbytes
19 grams (2/3 oz.)

Barracuda
Three 3.5” Discs
500 Gbytes
740 FMD’s

2004

Savvio
Two 2.5” Discs
73 Gbytes
1 lb.
What goes into a hard disc drive?
About Recording Head Technology

Wafer Fabrication

• Creation of electromagnet using:
  • Photolithography
  • Plating
  • Vacuum deposition

Head/Slider Manufacturing

• Wafer is cut into individual electromagnets:
  • Slicing
  • Lapping
  • Ion milling
  • Carbon coating
Really small scales

The head (slider) moves at \( \sim 60 \text{ MPH} \) while the head is flying at \( \sim 10 \text{ nm} \) over the disc!

If you scale everything up:

If that head were a 747 jet and the disc the earth, the plane would be flying at 800 times the speed of sound, less than an inch off the ground and counting every blade of grass as it rocketed past.
Head Disc Interface: Really small scale sizes

Typical passive head flies above disc at less than 12 nm and ~ 2nm with actuation!

Head-disc spacing is Smaller than this line!

Average
smog
particle
2.5 um
diameter

Average
smoke
particle diameter
6 um

Fingerprint
smudge

Average
human hair
diameter  100 um
The read write head and the features of the head-disc interface are measured using several tools.

- **1 mm to 10 um**: Optical microscope for a large view of the entire head.
- **10 um to 0.1 um**: Scanning Electron Microscope (SEM) to see small features such as the reader and the writer.
- **Surface roughness < 1nm**: Atomic Force Microscope (AFM) to see surface topography of the head and disc.
Head Disc Interface: Physics on small scales

- Physics in the head-disc interface. Need understanding, models and measurements!
  - Nano-scale fluid modeling: How does air pressurize in nanoscale spaces?
  - Thermal deformation of the head: How can we actuate using heat?
  - Wear: How does the head interact with the disk and what happens?
  - Interface lubrication: How does such a thin layer of lube behave at such high shear?

- I have worked to develop heat based actuator for the head.
  - Develop fundamental physical models for head transfer for rarefied gases.
  - Actuation efficiency is ~ 1 Å/mW to control head-disc spacing to ~2nm

- I am currently studying how frictional heating is generated when the head hit the disk.

Diagram of a head flying over a disk [Y. Goto et al., 2005]

Fly height change as a function of applied writer current [Liu and Han, 2002].
Measurements: Contacting small

How can we study the frictional contact between the head and the disk when things are so small?

A: Use a wire! The resistance should change with the wire’s temperature.

\[ dR = \alpha R_0 \Delta T \]

Using this we can see the temperature increase from the heater actuator and from frictional heating.

To measure this needed to use computer control test equipment.
- Scope, function generator, current source, etc.
- GPIB, Serial, USB
- LabView, LabWindows, Matlab and Python

Analysis using digital signal processing. Drive the input at a known frequency and listen to the output only at that frequency.
We need to resolve dynamics of contact between the head and the disc when a small ~100 um^2 area of the head contacts the disc.

-Acoustic Emission (AE): Measure acoustic vibrations from contact. (20k - 500k Hz).
-Laser Doppler Vibrometer (LDV): Laser to measure amplitude of vibrations (0.1 - 3 nm)
-Friction sensor: Measure shear forces from the small area on the head hitting the disc. (0.01 - 1 mN or 1- 100 mgf)
-The reader: The amplitude of the signal from the reader can measure clearance changes of ~ 0.2 nm.