The Power of the Universe on Earth: Plasma Physics and Fusion Energy

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What is a plasma?
Why should we care?
Where are the questions?

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“…if you tell me I listen … if you teach me I learn … if you involve me I remember …”
(Jim Diaz quoting Ben Franklin)

Outreach and education are intrinsically linked
Stimulate interest and you will stimulate learning

Scientists at all levels must get involved in sharing their science
Elementary schools
High schools
University/College
Teacher training
General Outreach

In all of these settings: Outreach, materials development and direct educational efforts are underway

1999 APS/DPP Outreach/Expo
Courtesy of Carol Danielson
Outline

What is a plasma?
Where do we find them?
Why are we interested in them?
  Astrophysics
  Plasmas all around us
  Fusion energy
More on fusion energy.
Charged particles moving in a magnetic field.
Turbulence

Picture courtesy of Jan Curtis
http://climate.gi.alaska.edu/Curtis/curtis.htm
What is a plasma?

A plasma is an ionized gas. Plasma is called the “fourth state of matter.” More than 99% of the known mass of the universe is in the plasma state. ‘Plasma’ was coined by Tonks and Langmuir in (1929):

“...when the electrons oscillate, the positive ions behave like a rigid jelly...”
Where do we find plasmas?

Examples of plasmas on Earth:
- Lightning
- Neon and Fluorescent Lights
- Laboratory Experiments

Examples of astrophysical plasmas:
- The sun and the solar wind
- Stars, interstellar medium
Astrophysical plasmas

The Sun

Catseye Nebula

http://bang.lanl.gov/solarsys/

http://www.stsci.edu:80/
MyCn18, a young planetary nebula located about 8,000 light-years away.

Galaxy NGC 4414, is 19.1 megaparsecs or about 60 million light-years.

Pictures courtesy of NASA
http://nssdc.gsfc.nasa.gov/photo_gallery/
Plasmas on Earth

Laboratory Experiments

Lightning

http://FusEdWeb.pppl.gov/
Why are we interested in plasmas?

**Fusion Energy**
Potential source of safe, abundant energy.

**Astrophysics**
Understanding plasmas helps us understand stars, stellar evolution and the evolution of the Universe.

**Upper atmospheric dynamics**
The upper atmosphere is an important plasma.

**Plasma Applications**
Plasmas can be used to build computer chips and to clean up toxic waste.
Plasmas around us

Plasma processing
Computer chips
Surface modification

Lighting

Pictures from
Plasmas: The 4th State of Matter

Courtesy of University of Wisconsin, Madison
Photographer Bruce Fritz
Plasmas around us

Plasma displays
Decontamination
Plasma Thrusters

Plasma torch from the Plasma Technology Research Center

Electrograph Plasma Display
http://www.electrograph.com/detail.asp
The solar wind (a plasma) interacts with the Earth’s magnetic field.

The sun emits mass in the form of plasma at velocities of up to 500 km/s.

This solar wind causes the Earth’s magnetic field to compress creating a shock wave called the Bow wave.

*From* *Stars*, *James Kaler*
Interactions between the earth’s magnetic field and a plasma can have spectacular results

The northern lights (aurora borealis)

Photo by David Fritts
http://dac3.pfrr.alaska.edu:80/~pfrr/AURORA/INDEX.HTM
Mass goes into energy in a fusion reaction.
Properties of plasmas

A collection of positively and negatively charged particles.

Plasmas interact strongly with electric and magnetic fields.

Plasmas support many different types of waves and oscillations.

http://demo-www.gat.com/
Much of plasma physics research has been motivated by the goal of controlled fusion energy. Fusion energy is a form of nuclear energy which is emitted when two light nuclei combine to form a single more stable nuclei. The sun and stars derive their energy from fusion.
# Why is Fusion power needed?

## 1990 Energy use per capita

<table>
<thead>
<tr>
<th>Country</th>
<th>Consumption (kW-h/capita)</th>
</tr>
</thead>
<tbody>
<tr>
<td>US</td>
<td>12000</td>
</tr>
<tr>
<td>Developed World Avg.</td>
<td>6000</td>
</tr>
<tr>
<td>World Avg.</td>
<td>1500</td>
</tr>
<tr>
<td>China</td>
<td>500</td>
</tr>
<tr>
<td>India</td>
<td>250</td>
</tr>
</tbody>
</table>

## Projected change in consumption by increasing to world average

<table>
<thead>
<tr>
<th>Country</th>
<th>Energy Use 1990 (GW)</th>
<th>Energy Use 2020 (GW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>China</td>
<td>120</td>
<td>500</td>
</tr>
<tr>
<td>India</td>
<td>65</td>
<td>450</td>
</tr>
</tbody>
</table>

## If fossil Catastrophe Looms

Fuel and waste for coal plants (most readily available energy source) vs D-T fusion plant

<table>
<thead>
<tr>
<th>Daily Fuel Consumption</th>
<th>Daily Waste Production</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>1,000 Megawatts</strong></td>
<td></td>
</tr>
<tr>
<td><strong>Coal Plant</strong></td>
<td><strong>D-T Fusion Plant</strong></td>
</tr>
<tr>
<td>9,000 T. Coal</td>
<td>1.0 LB D$_2$</td>
</tr>
<tr>
<td>30,000 T. CO$_2$</td>
<td>3.0 LB Li$^6$</td>
</tr>
<tr>
<td>600 T. SO$_2$</td>
<td>(1.5 LB T$_2$)</td>
</tr>
<tr>
<td>80 T. NO$_2$</td>
<td></td>
</tr>
<tr>
<td></td>
<td>4.0 LB He$^4$</td>
</tr>
</tbody>
</table>

http://www.pppl.gov
Deuterium and tritium combine to form helium, a neutron and fusion energy.
High temperatures and densities are needed

http://lasers.llnl.gov/lasers/education/talk.html
Hot plasmas are confined with gravitational fields in stars. In fusion energy experiments magnetic fields and lasers are used to confine the hot plasma.
What must be achieved to obtain fusion energy?

Contain a high temperature, $T$, high density, $n$, plasma for a long enough time, $\tau$, to achieve ignition (power out $>>$ power in).

A measure of plasma performance is thus given by:

$$nT\tau$$

density $\times$ temperature $\times$ confinement time
Two major approaches to fusion (D–T)

**Magnetic confinement**
- Temperature $\approx 10^8$ °C (10 keV)
- $\eta \tau \approx 10^{15}$ Atoms $\cdot$seconds / cm$^3$
- $\tau \approx 10$ seconds (magnetic “bottle”)
- $\eta \approx 10^{14}$ Atoms / cm$^3$ (10$^{-5}$ times the density of air)

**Inertial confinement**
- Temperature $\approx 10^8$ °C (10 keV)
- $\eta \tau \approx 10^{15}$ Atoms $\cdot$seconds / cm$^3$
- $\tau \approx 3 \times 10^{-11}$ seconds (microexplosion, inertial “bottle”)
- $\eta \approx 3 \times 10^{25}$ Atoms / cm$^3$ (12 times the density of lead!)
- $\sim 1000$ times the density of liquid DT!)
Power Plant Schematic
The Inertial Confinement Fusion Concept

**Laser energy**

**Blowoff**

**Inward transported thermal energy**

**Atmosphere formation**
Laser beams rapidly heat the surface of the fusion target forming a surrounding plasma envelope.

**Compression**
Fuel is compressed by the rocket-like blowoff of the hot surface material.

**Ignition**
During the final part of the laser pulse, the fuel core reaches 20 times the density of lead and ignites at 100,000,000°C.

**Burn**
Thermonuclear burn spreads rapidly through the compressed fuel, yielding many times the input energy.

http://www-lasers.llnl.gov/lasers/nif/nif_ife.html#fusion
Particles in a Magnetic field

Picture courtesy of NASA   http://nssdc.gsfc.nasa.gov/photo_gallery/
Controlling fusion with magnetic fields

Most magnetic confinement devices in use today have a toroidal shape. Large magnetic fields are created by driving currents through coils wrapped around the torus.

http://demo-www.gat.com/
Joint European Torus:
the largest confinement device ever built

http://www.jet.uk/
Need to control temperature and density

We need the core hot enough for fusion, yet the edge cool enough not to melt the walls
But nature abhors gradients

Whenever a slope (gradient) gets too steep, nature finds a way to flatten it out

Mountains get eroded
sand and snow avalanche
turbulence grows to flatten steep slopes in plasmas

We need to control the turbulence
Turbulence moves things down the slope

The turbulent swirls (eddyes) move the heat and density toward the edge
Challenges on the path to Fusion

Heating
Fueling
Confinement

Plasma physics is on the leading edge of technology
Turbulence is everywhere in nature

Turbulent transport is one of the main methods for relaxing gradients


http://info.pitt.edu/~maarten/work/soapflow/soapjgps/dense.turb.JPG
Progress towards fusion energy

Summary

Plasmas are ubiquitous in our world
Science can indeed be both fun and important
Important discoveries and developments come from unexpected places so….

We must encourage people (especially young people) to explore the world around them

Stimulating interest stimulates learning which stimulates discovery and innovation which stimulates the economy
Web References

Fusion energy and plasma educational sites

http://FusionEd.gat.com/  General Atomics
http://lasers.llnl.gov/lasers/education/ed.html  Lawrence Livermore National Laboratory
http://www.jet.uk/  Joint European Torus
http://ffden-2.phys.uaf.edu  My home page at the Univ. of Alaska - Fairbanks

Astrophysics sites

http://umbra.nascom.nasa.gov/spd/  NASA Space Science
http://www.seds.org/billa/tnp/  The Nine Planets
http://www.stsci.edu:80/  Space Telescope Science Institute
http://bang.lanl.gov/solarsys/  Views of the Solar System
http://www.gi.alaska.edu/  Geophysical Institute (Aurora and Sprite info)
http://www.sec.noaa.gov/  NOAA Space weather site

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