A2299
The Search for Life in the Universe
Fall 2015

So far: Big Bang → Elements → Stars → Planetary Systems
Today: Earth and its solar system environment: issues for life

Two branches of investigation in astrophysics and astrobiology

Fundamental physics and the nature of the universe

Understanding (and inventing) complexity
Planetary systems
Life (natural and artificial)
Quarks to Cosmos: Some Big Questions

- What is dark matter?
- What is dark energy?
- Did Einstein have the last word on Gravity?
- How do cosmic accelerators work and what are they accelerating?
- What are the new states of matter at exceedingly high density and temperature?
- Is a new theory of light and matter needed at the highest energies?

From Quarks to Complexity

- How does a ‘simple’ big bang turn into a universe with stars, planets and life?
- How do planetary systems form?
- How common are planetary systems?
- What is the role of interstellar molecules in jump starting life on planets?
- What forms of life exist?
- How common are Earth-like conditions?
- Is intelligent, technological life common or rare?
The Earth and its Evolution

Important features of the Earth relevant to the formation of life and the apparent increase in complexity of life:

- Large quantity of water in sustained liquid state
- Impacts (debris: comets, asteroids, TNOs)
- Continents
- Plate tectonics (volcanism)
- Magnetic field (shielding from cosmic rays)
- Stability of the Earth’s spin axis (presence of the Moon)
- Orbital stability (the other planets)
- Greenhouse effect
- Stability of the solar luminosity

These and other factors are discussed in *Rare Earth* and used to argue that complex life like ours is exceedingly rare in the Galaxy (in spite of ~ $10^{11}$ sun-like stars).

Science Magazine

Good news, earthlings: The planet Mercury probably won’t kill us

Mercury may crash into Venus, but Earth is probably safe, if a new study is right.

By Kon Croadell  |  18 September 2015 3:45 pm  |  21 Comments

One day, Mercury could slam into Earth, obliterating all life on our planet.
The Earth and its Evolution

Possible fallacies of the Rare Earth argument:

- Implicit is the assumption that the path by which life has evolved on Earth is the only path that would lead to creatures like ourselves.
- Perhaps there are multiple trajectories that a biosphere can take, contingent on chance events: volcanism, impacts, fraction of surface water, distance from host star, spin rate and spin stability, etc.
- Nature is more inventive than the human mind!
- The large numbers of stars and planets in the Milky Way alone provide a huge number of biological experiments by nature for the last ~ 13 Gyr (and continuing).

FORMING A SOLAR SYSTEM
Star Formation in the Galaxy

Star formation is ongoing.
About 1 to 10 new stars formed each year in the Milky Way.
The rate of new star formation is much larger in some galaxies and was also much larger at earlier times (10 billion years ago).

The Eagle Nebula (HST image)

\( \beta \) Pictoris
A Nascent Solar System

\[ \begin{align*}
24.3 \mu m \\
18.3 \mu m \\
12.3 \mu m \\
11.7 \mu m \\
8.7 \mu m 
\end{align*} \]
Planet Formation

- Collapse of the protoplanetary disk from an interstellar gas cloud, while the inner part was collapsing to form the sun.
- Formation of planetesimals to form protoplanets in about $10^5$ yr in the inner solar system, and $10^7$ yr in the outer SS.
- Orbits stabilize as bigger objects deflect smaller ones or collisionally merge with them.
- “Final” configuration of planetary orbits after a few hundred million years.
- Cleanup: ongoing…

NB: Mercury, Venus and Mars will be engulfed by the Sun’s atmosphere in its red-giant phase

Solar System Formation

Prime ingredients:
- Metals for solar abundances and for rocky planets.
- Gas cloud that can collapse to form a protostar and protoplanetary disk.
- Magnetic fields to help redistribute angular momentum.
Ubiquity of Disks and Jets in Astrophysics

1. Accretion disks around supermassive black holes.
   • Centers of galaxies.
   • Disk temperature related to GPE of SMBH.
   • Disks are ‘fed’ episodically by gas and stars from the host galaxy.

2. Accretion disks around stellar mass BH, NS, and white dwarfs (10 M_☉, ~1.4 M_☉ and <1.2 M_☉, respectively).

3. Accretion disks around protostars.

In all cases, radiation has to be emitted for material to move inward (virial theorem) and angular momentum has to be transferred outward (angular momentum barrier).

Active Galactic Nuclei
Accretion onto Compact Objects (WD, NS, BH)

Fig. 1 An artist’s impression of a low-mass BHXRB. The major components of the binary, accretion flow, and outflows are indicated.

R Fender, and T Belloni Science 2012;337:540-544
Proto star, disk and jet

Image credit: Brooks/Cole Thomson Learning

Protoplanetary Disks and Jets

Structure of a Protoplanetary Disc
New Star + Protoplanetary Disk: Basic Features

- Envelope
- Disk
- Protostar
- Jet/wind/outflow

Interstellar cloud
~ pc or more in size
Net angular momentum
[universe likely has no net angular momentum]

Collapse $\|\|$ to angular momentum vector
requires radiation only (a la virial theorem)

Collapse inward requires
1. Radiation
2. Removal of angular momentum
3. Ultimately requires dissipation of magnetic field

Viscosity allows gas+dust in the inner disk transfer angular momentum outward

Viscosity is from gas collisions + turbulence in the gas, including the magnetic field

Magnetic pressure:
$P \sim B^2/8\pi$
B grows as cloud collapses and can aid removal of angular momentum
Ohmic dissipation of field: Currents dissipate.
Angular Momentum Barrier

Object in circular orbit: we have the usual potential, kinetic, and total energy

\[
PE = -\frac{GMm}{r} \quad KE = \frac{1}{2}mv^2 = \frac{GMm}{2r} \quad E = \frac{1}{2}PE = -\frac{1}{2}KE
\]

The potential energy \( V(r) = PE \) is a negative going well.

For an object moving with arbitrary velocity we can write an effective potential

Let \( v_\phi = \) azimuthal velocity and \( v_r = \) radial velocity

The object can be on an elliptical, hyperbolic, or parabolic orbit.

Let \( J = \) angular momentum = \( mv_\phi r \)

Then the energy of the particle can be written as

\[
E = \left(\frac{1}{2}\right)m v_r^2 + \frac{J^2}{2mr^2} - \frac{GMm}{r}
\]

The last two terms comprise an “effective” potential

\( V(r) = \frac{J^2}{2mr^2} - \frac{GMm}{r} \) where the first term is a centrifugal barrier at small \( r \)

Effective Potential with Angular Momentum

![Graph illustration of effective potential with angular momentum](image)
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Magnetic Fields and Structure Formation
**Magnetic fields**

- Neutron stars: $10^8 - 10^{14}$ G
- White dwarfs: up to $10^8$ G
- Sun: ~ kG sunspots
- Earth: ~ 1 G (100 μTesla)
- Interplanetary medium: ~ 10 μG
- Interstellar medium: ~ few μG
- Intergalactic medium: ~ $10^{-9}$ G
Jet collimated by magnetic field in an active galactic nucleus

Galaxy-scale magnetic fields
Milky Way: view from inside
Polarization of thermal radiation

Aligned grains

E ⊥ B

Polarized radiation
Cosmic ray intensities (left) compared with predictions (right) from IBEX. The similarity between these observations and predictions—as evidenced by the similar color regions—supports the local galactic magnetic field direction determined from IBEX observations made from particles at vastly lower energies than the cosmic ray observations shown here. The blue area represents regions of lower fluxes of cosmic rays. The gray and white lines separate regions of different energies—lower energies above the lines, high energies below.

Read more at:
Relevance of Magnetic Fields

- Magnetic fields are important for formation and evolution of protoplanetary disks (transferring angular momentum so that the disk can contract).
- Cosmic rays are trapped in the Galaxy by its magnetic field; some CRs cause mutations in the biosphere.
- Earth’s magnetic field protects the biosphere from most (but not all) CRs and from particles from the Sun.
- Navigation:
  - Some birds (magnetite in their brains).
  - Human.