A1199
Are We Alone?
The Search for Life in the Universe
Summer 2019

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Reminder: HW2 due Wednesday July 10th.
So far: Cosmology, galaxies, stars, planets
Now: Our solar system
New Star + Protoplanetary Disk: Basic Features

- Envelope
- Disk
- Protostar
- Jet/wind/outflow
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 $M_\odot$, ~1.4 $M_\odot$ and <1.2 $M_\odot$, 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

Inner Structure of an Active Galaxy

- Relativistic Jet
- Supermassive Black Hole
- Accretion Disk
- Opaque Torus (Inner Regions)

FR Class I source: radio galaxy 3C31

Radio Galaxy 3C31 a NSC 388
Copyright NRAO/AUI 2006

FR Class II source: quasar 3C175
Accretion onto Compact Objects (WD, NS, BH)
Neutron star as a radio pulsar (rotation driven)

http://astronomy.nmsu.edu/tharris/ast110/class20.html
Galaxy-scale magnetic fields
The Galactic Center at radio wavelengths

MeerKAT inaugural image, 2 degrees across.
Magnetic Field of Planets

<table>
<thead>
<tr>
<th>Planet</th>
<th>Tilt of Rotation Axis</th>
<th>Tilt of Magnetic Axis</th>
<th>Offset of Magnetic Axis</th>
<th>Field at Equator</th>
<th>Magnetosphere</th>
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<tbody>
<tr>
<td>Earth</td>
<td>23°</td>
<td>12°</td>
<td>8%</td>
<td>31,000 nT</td>
<td>10 R_{Earth}</td>
</tr>
<tr>
<td>Jupiter</td>
<td>3°</td>
<td>-10°</td>
<td>10%</td>
<td>428,000 nT</td>
<td>65 R_{Jupiter}</td>
</tr>
<tr>
<td>Saturn</td>
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<td>-0°</td>
<td>5%</td>
<td>22,000 nT</td>
<td>20 R_{Saturn}</td>
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<tr>
<td>Uranus</td>
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<td>-59°</td>
<td>31%</td>
<td>23,000 nT</td>
<td>18 R_{Uranus}</td>
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<tr>
<td>Neptune</td>
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<td>-47°</td>
<td>55%</td>
<td>13,000 nT</td>
<td>25 R_{Neptune}</td>
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</tbody>
</table>
Cosmic Rays

- Relativistic particles with $v \sim c$.
- Energies: $E = \gamma mc^2$.
  (where $\gamma = 1/(1-v^2/c^2)^{1/2}$ = Lorentz factor $>> 1$)
- Most are Galactic in origin from acceleration in supernova shocks.
- The highest energy CRs are likely produced in AGNs.
- Some might be from dark-energy particle annihilation.
- CRs may be involved in mutations (typical bond energies $\sim 1$ eV).
- The Earth’s magnetic field and atmosphere protect us from most CRs.
Cosmic rays and magnetic fields

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.

Auroras
Magnetic Flip-Flops

Rocks become magnetized in the direction of the Earth's field.

Older rocks preserve a record of field reversals.

Magnetic Reversal Time-Scale:
- Bruhnes normal epoch: 0.0 million years
- Matuyama reversal epoch: 1.0 million years
- Gauss normal epoch: 2.0 million years
- Gilbert reversal epoch: 4.0 million years
- Age in Millions of years:
  - 0.0
  - 1.0
  - 2.0
  - 3.0
  - 4.0
  - 5.0
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.
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...
Planet Formation
This simulation:

- Starts with $3 \, M_{\text{Earth}}$ planet in a viscous protoplanetary disk.
- Planet grows to $10 \, M_{\text{Jupiter}}$
- Orbit decays due to disk interaction.
- Gap opening: planet interaction, angular momentum exchange clears orbit.
- Once gap cleared, drag is low; accretion rate is small; planet holds position relative to disk.
Protoplanetary Disks
HL Tauri: Planet formation in disks

The protoplanetary disk surrounding the young star HL Tauri.

(NOT an artist’s impression!)

These ALMA observations reveal substructures within the disc that have never been seen before and even show the possible positions of planets forming in the dark patches within the system.

Credit: C. Brogan et al. 2014, ALMA (ESO/NAOJ/NRAO)
A planet being born: PDS 70b

PDS 70: a 10-million-year-old dwarf star about 370 light-years from Earth.

PDS 70b: Newly forming planet.

Miriam Keppler et al., July 2018, results from SPHERE instrument at ESO/VLT.
Protoplanetary disks: Proplyds

HST WFPC-2 view of a small portion of the Orion Nebula reveals five young stars. Four of the stars are surrounded by gas and dust trapped as the stars formed, but were left in orbit about the star. These are possibly protoplanetary disks, or “proplyds”, that might evolve on to agglomerate planets.
Evolution of two neighboring planets in a protoplanetary disk.
Time and tide wait for no man...

GRavitational Interactions and Tidal Forces
Hill Sphere

- The approximate limit to a secondary’s (Moon’s or planet’s) gravitational dominance is given by the extent of its Hill sphere:

\[ R_H \approx a \left( \frac{m_q}{3(m_p + m_q)} \right)^{1/3} \]

- A test particle located at the boundary of the Hill sphere is subject to a gravitational force from the planet comparable to the tidal difference between the force of the Sun on the planet and that on the test body.

- The Hill sphere stretches out to the L1 Lagrange point.

- All planet-centric orbits within the Hill sphere are stable over long periods of time, this is where we find all natural satellites.
Hill Sphere

L1–L4 = Lagrangian points.
Defined by balance of gravity and centrifugal forces.

The Hill spheres are the circular regions surrounding the two large masses (Earth and sun radii are not to scale.)

The Hill sphere is the region of gravitational influence.

Earth’s Hill sphere ~ 0.01 AU

A contour plot of the effective potential of a two-body system due to gravity and inertia at one point in time.

Various spacecraft have been placed at L1 and L2.
Lagrange points: restricted three-body problem

**Sun-Earth:**
- L₁: Sun observing satellites: SOHO
- L₂: Astronomical satellites: WMAP, Herschel, GAIA, JWST, PLANCK

L₁ and L₂ are not stable; spacecraft actively control their orbits around these points, not exactly at the points.

**Sun-Jupiter:**
- L₄ and L₅: Trojan satellites
- L₁, L₂, L₃: Orbits are not stable
James Webb Space Telescope

About Webb’s Orbit

The James Webb Space Telescope will observe primarily the infrared light from faint and very distant objects. But all objects, including telescopes, also emit infrared light. To avoid swamping the very faint astronomical signals with radiation from the telescope, the telescope and its instruments must be very cold. Therefore, Webb has a large shield that blocks the light from the Sun, Earth, and Moon, which otherwise would heat up the telescope, and interfere with the observations. To have this work, Webb must be in an orbit where all three of these objects are in about the same direction. The answer is to put Webb in an orbit around the L2 point.

The L2 orbit is an elliptical orbit about the semi-stable second Lagrange point. It is one of the five solutions by the mathematician Joseph-Louis Lagrange in the 18th century to the three-body problem. Lagrange was searching for a stable configuration in which three bodies could orbit each other yet stay in the same position relative to each other. He found five such solutions, and they are called the five Lagrange points in honor of their discoverer.

In three of the solutions found by Lagrange, the bodies are in line (L1, L2, and L3); in the other two, the bodies are at the points of equilateral triangles (L4 and L5). The five Lagrangian points for the Sun-Earth system are shown in the diagram below. An object placed at any one of these 5 points will stay in place relative to the other two.

In the case of Webb, the 3 bodies involved are the Sun, the Earth and the Webb. Normally, an object circling the Sun further out than the Earth would take more than one year to complete its orbit. However, the balance of gravitational pull at the L2 point means that Webb will keep up with the Earth as it goes around the Sun. The gravitational forces of the Sun and the Earth can nearly hold a spacecraft at this point, so that it takes relatively little rocket thrust to keep the spacecraft in orbit around L2.

Other infrared missions have selected an L2 orbit, like WMAP and H2L2. For a more detailed explanation of the Lagrangian points, please see the WMAP discussion of this orbit.

Here are a few graphics that illustrate how far away Webb will be. It will take Webb rough 30 days to reach the start of its orbit of L2.
Hill Radius ($R_H$)

A non-rigorous but conceptually accurate derivation of the Hill radius can be made by equating the orbital angular speed of the orbiter around a body (i.e. a planet) and the orbital angular speed of that planet around the host star. This is the radius at which the gravitational influence of the star roughly equals that of the planet.

$$\Omega_{\text{planet}} = \Omega_*$$

$$\sqrt{\frac{GM_{\text{planet}}}{R_H^3}} = \sqrt{\frac{GM_*}{a^3}},$$

where $R_H$ is the Hill radius, $a$ is the semi-major axis of the planet orbiting the star. With some basic algebra:

$$\frac{M_{\text{planet}}}{R_H^3} = \frac{M_*}{a^3}$$

giving a Hill radius of:

$$R_H = a \left(\frac{M_{\text{planet}}}{M_*}\right)^{1/3}.$$
Hill Sphere and Bode’s Law

The spacing between planets increases with greater distance from the Sun.

This is consistent with the Hill sphere of any given planet where

$$R_H = a \left(\frac{m_p}{M}\right)^{1/3}$$

$$a = \text{orbital radius}$$

Hill Sphere and Protoplanetary Disks

- Planetesimals form from dust grains that stick together.
- Eventually, the planetesimal grows into a protoplanet. Gravity is large enough to influence accretion of dust, gas.
- The annular zone around the star in which the protoplanet can accrete is 2 x Hill radius wide; this is the “feeding zone”.
- The Hill radius grows as the planet’s mass increases but ultimately material in the feeding zone is consumed.
- At that point further growth of protoplanets occurs by orbit crossings induced by gravitational deflections and other processes.
Lagrange points: restricted three-body problem

Sun-Earth:
- $L_1$: Sun observing satellites: SOHO
- $L_2$: Astronomical satellites: WMAP, Herschel, GAIA, JWST, PLANCK

$L_1$ and $L_2$ are not stable; spacecraft actively control their orbits around these points, not exactly at the points.

Sun-Jupiter:
- $L_4$ and $L_5$: Trojan satellites
- $L_1$, $L_2$, $L_3$: Orbits are not stable
Asteroids at L4 and L5 in Jupiter’s orbit:
- Trojans
- Greeks
Main Asteroid Belt Distribution

Kirkwood Gaps

Asteroids (per 0.005 AU bin)

Semi-major Axis (AU)

(JPL)
Putting it together...
Putting it together…

• Stars and planets form out of molecular clouds.
• The Jeans mass is the minimum mass ‘core’ or sub-cloud that can collapse. It depends on the temperature and size of the core.
  → Molecular clouds are cold and dense (by necessity) so the Jeans mass ~few solar masses.

• Collapse requires getting past the ‘centrifugal barrier’ imposed by angular momentum.
  → Mass in the inner parts of the region must transfer its angular momentum to the outer parts.
  → This occurs via magnetic fields that thread the gas and also by jets that carry away some of the angular momentum.
Putting it together…

• Disks and jets are generic aspects of collapse and accretion on galactic scales (super-massive black holes [M87]) and protostars. (Also NS, BH.)

• Planets form ‘bottom-up’:
  • Rocky planets: planetesimals → proto-planets → planets.
  • Gas giants: rocky cores + accreted gas.

• The ‘final’ configuration of planets is related to the Hill sphere size of each planet and gravitational encounters in the stages leading to the final configuration.