Other Worlds in Space: modern astronomy from the perspective of *Exoplanets*

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What we are doing in this class: a survey of (much of) contemporary astronomy, but with emphasis on an exciting, recent wrinkle: exoplanets
A meditation on the study of astronomy:

“We want to feel, not just observe, what the heavens offer…”

John Goss, Astronomical League

The motivating idea for this class

- We live on a planet (Earth) in the solar system
- All the planets orbit (and are controlled by) the Sun
- The Sun is a star
- The night sky is filled with stars
- Are there planets around some (or all) of those stars?
- Are some of those planets like the Earth?
- In 1995, we suspected the answer to (last 2 points) was yes, but we had no definite examples
A mental goal of the class: an Earthlike planet around another star
A sneak preview of where we are headed: the situation with exoplanets as of Dec. 2017

Exoplanet Discoveries

Total confirmed exoplanets = 3,567

Total Kepler = 2,525
Let’s get back to basics: if we are going to understand exoplanets, we need to start with our own solar system.

“I seem to remember from junior high that there were others...”
Jupiter, Saturn, Uranus, and Neptune are all further out
The Solar System: in school we learn about the 8 (or 9) planets that orbit the Sun.

In solar system, the planets are where life is (at least in one case).
The Solar System is our best chance to study planets in detail (and learn some interesting astronomy, too)
The Earth as a Planet
Main aspects of the Earth

- Surface temperature: about what is outside
- The atmosphere
- Liquid water
Chemical composition of the Earth’s atmosphere

- Nitrogen (N2): 78%
- Oxygen (O2): 21%
- Argon: 1%
- Water vapor: 0 - 4%!
- Carbon dioxide (CO2): 0.040 %

By solar system standards, the Earth’s atmospheric composition is unusual; the oxygen content is extremely unusual.
A measure of how “thick” an atmosphere is: atmospheric pressure

- Atmospheric pressure is weight of overlying layers of air
- In physics has **units** of Force/(unit area) = Newtons/(square meter) = Pascals
- Atmospheric pressure at sea level = 1.013E+05 Pa
- Also called “one atmosphere”
Liquid water on the surface of the Earth

The temperature and pressure at the surface of the Earth are close to the “Triple Point” of water (H2O), conditions where water simultaneously is in equilibrium in the solid, liquid and gaseous states. This permits the hydrological cycle on Earth.

The hydrological cycle and the triple point of water are almost certainly crucial for the existence of life on Earth.

Amazingly, the Earth is not unique among solar system objects in having a “hydrological” cycle. Stay tuned.
Overall Physical Structure of the Earth (the Earth as a ball)

- Mass = 5.98E+024 kilograms
- Diameter = 12756 kilometers (7920 miles)
- Average density = 5.52 g/cc
- Denser than almost all rocks: heavy stuff in Earth’s interior
How do the other planets “stack up” next to the Earth?
In our Solar System, the planets are so different, we have to put them in two groups.

Rough sizes of the *terrestrial planets*.

This picture was known 50 years ago.
Where are Mercury and Venus in the night sky?

Very easy to find!
Venus...closer and bigger. Expect more to see

Current distance 1.61 AU, angular diameter 10.3 arcseconds. *Why can’t we see anything on the surface?*
Venus... Earth’s twin

Venus is perpetually overcast. You cannot see the surface from Earth. Only the top of a cloud layer
Similarities between Earth and Venus?

Fact that Earth and Venus are so similar in physical properties (size and mass), and that one cannot see the surface was conducive to imagination.
Seeing through the clouds of Venus with Radio Astronomy!
Radio astronomy and application of laws of physics allow us to measure the surface temperature of Venus (done first in the late 1950s)

- Surface temperature is 730K
- That corresponds to 855 degrees Fahrenheit
- No longer “Earth’s twin”
- What is responsible for this sort of temperature?
- Physics tells us!
What the surface of Venus looks like
And now, a similar view of Venus, thanks to the Magellan orbiter.
Remaining questions about Venus

• Why is the surface temperature so high?
• **Hint:** it has a dense, carbon dioxide atmosphere
• Did Venus ever have oceans like the Earth?
• If it did have them, where did they go? (See article from Sky and Telescope, April 2008)
Lessons of Venus for exoplanet studies

- A planet can be the “right size”, and nearly in the “right place”, but still be completely unsuitable for life
Moving out in the solar system...Mars
Mars...start with the orbital parameters

- Semimajor axis: 1.524 AU
- Orbital Period: 1.88 years
- Eccentricity: 0.093
- Best *opposition* since 2003 this summer (late July); take advantage of the chance to see Mars through a telescope
Average physical characteristics of Mars
What could we tell before the age of spacecraft and large telescopes?

Observations showed features on surface ("canals of Mars")
1962 Mars Map
Pre-space age telescopic observations yielded a number of intriguing features

- Seasonal variations in features
- Obliquity similar to Earth (25.0 degrees versus 23.5 degrees)
- Polar caps that change with the season
- Rotation period 24h 37m
- Clouds in an atmosphere

Led to speculation that Mars might be an Earthlike planet with primitive life (lichens)
By the 1960s it was known that the circa-1900 view of an Earth-like Mars with higher life forms could not be right; the atmosphere on the surface of Mars is about 0.7 % the sea-level pressure on Earth. Water cannot exist in liquid form under those conditions.

The average surface temperature on Mars is also about 100 degrees Fahrenheit below.
The atmosphere of Mars: 95% CO2

Most of the rest is nitrogen (diatomic molecular)

The chemical composition of Martian atmosphere is like Venus, not the current Earth

(But like the early Earth)
Robotic Exploration of Mars

We have learned an incredible amount about Mars in the past few decades.
An illustration of the fascinating results brought to us by robot spacecraft
A major result: apparent ancient water channels
Determining the Ancient History of Mars

What its present surface tells us
The central mystery of Mars since the 1970s

• The present climate of Mars is such that liquid water cannot last long
• Orbiting spacecraft show apparent evidence of flowing water channels (rivers and larger) in landscapes that formed 3–4 billion years ago
• How are these two (apparently) contradictory results to be reconciled?
These observations led to the idea of the “Warm, Wet Mars”

Mars 3.8 billion years ago?

Since 1990s, clear that the key is to land on the surface, do geology
The key to determining the ancient climate of Mars (and implications for life); robot geological laboratories

Curiosity
The Mars Science Laboratory and Gale Crater

Clay deposits at bottom of central mountain
The destination for “Curiosity”
What have we learned from the MERs, “Mars Phoenix”, and Mars Science Laboratory

• It now seems clear that there were standing bodies of water for long periods of time early in Martian history
• Evidence is presence of hematite, jarosite, and other minerals that form in lakes or oceans
• Relative absence of carbonate rocks is due to alternative chemistry in acidic water
• **But**, apparently oldest rock strata do contain carbonate rocks and clay (montmorillonite)
• Mars Science Laboratory has found abundant mineralogical evidence for water in Gale Crater
• *Apparently* there were liquid water bodies on Mars in at least some locations (Gale Crater) long enough for life to have developed.
What happened to the atmosphere?

- The rocks found on the Martian surface required higher atmospheric pressures than presently exist.
- Mars must have lost its atmosphere.
- Can we find independent evidence for this? Yes! Finding of the *Maven* spacecraft.
- How long did it take to lose its atmosphere?---We’ll have to wait for the answer.
The El Dorado of future missions: Mars Sample Return

Stay tuned
What about the more distant planets in the Solar System?

What can they tell us about how planets formed, the nature of other solar systems?
Exploring further out in the Solar System

Jupiter, Saturn, and friends
Jupiter and Saturn: orbital characteristics

<table>
<thead>
<tr>
<th>Planet</th>
<th>a (AU)</th>
<th>P (yrs)</th>
<th>ecc</th>
<th>Incl (deg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jupiter</td>
<td>5.20</td>
<td>11.9</td>
<td>0.049</td>
<td>1.3</td>
</tr>
<tr>
<td>Saturn</td>
<td>9.58</td>
<td>29.4</td>
<td>0.057</td>
<td>2.5</td>
</tr>
</tbody>
</table>

What do they look like? Let’s start with Jupiter
Jupiter...largest planet in the solar system
Basic properties of Jupiter and Saturn

• Jupiter: 11.2 X diameter of Earth and 318 X mass
• Saturn: 9.5 X diameter of Earth and 95 X the mass
• Jupiter and Saturn: the “giant planets”
• Jupiter and Saturn are “all atmosphere”, and mainly hydrogen and helium
Jupiter and the Earth
The future exploration of Jupiter... Juno (arrived last summer)

Launch: August 5, 2011... Arrival at Jupiter: July 4, 2016
Juno Spacecraft

Juno’s Instruments

Gravity Science and Magnetometers
- Study Jupiter’s deep structure by mapping the planet’s gravity field and magnetic field
- Microwave Radiometer
  - Probe Jupiter’s deep atmosphere and measure how much water (and hence oxygen) is there
- JEDI, JADE and Waves
  - Sample electric fields, plasma waves and particles around Jupiter to determine how the magnetic field is connected to the atmosphere, and especially the auroras (northern and southern lights)
- UVS and JIRAM
  - Using ultraviolet and infrared cameras, take images of the atmosphere and auroras, including chemical fingerprints of the gases present
- JunoCam
  - Take spectacular close-up, color images

SPACECRAFT DIMENSIONS
- Diameter: 66 feet (20 meters)
- Height: 15 feet (4.5 meters)

For more information:
missionjuno.swri.edu & www.nasa.gov/juno

National Aeronautics and Space Administration
Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California
www.nasa.gov

NASA
The Juno spacecraft is giving us new insights into Jupiter

There is really no surface on Jupiter; the gas density and pressure get larger and larger, matter weirder and weirder.
Are Jupiter and Saturn planets or stars?

Jupiter as seen at infrared wavelengths

Jupiter emits 70% more radiation to space than it receives from the Sun. It has an “engine” inside
The Moons of Jupiter
Jupiter has many moons

- 12 when I started studying astronomy
- A standard textbook lists 38
- Most important are the 4 **Galilean** satellites, Io, Europa, Ganymede, Callisto
From Earth, it is difficult to learn too much about the Galilean satellites.

At opposition of Jupiter, the angular diameter of Ganymede is 1.7 arcseconds.

Pre space-age telescope observations revealed a little bit about size, reflectivity (albedo), and surface features.
### Basic data on the Galilean satellites

<table>
<thead>
<tr>
<th>moon</th>
<th>a (km)</th>
<th>P (days)</th>
<th>D (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Io</td>
<td>422,000</td>
<td>1.769</td>
<td>3630</td>
</tr>
<tr>
<td>Europa</td>
<td>671,000</td>
<td>3.551</td>
<td>3130</td>
</tr>
<tr>
<td>Ganymede</td>
<td>1,071,000</td>
<td>7.155</td>
<td>5280</td>
</tr>
<tr>
<td>Callisto</td>
<td>1,884,000</td>
<td>16.689</td>
<td>4840</td>
</tr>
<tr>
<td>MOON</td>
<td>384,000</td>
<td>27.32</td>
<td>3476</td>
</tr>
</tbody>
</table>

The largest Moon, Ganymede, has a diameter about 50 percent larger than our Moon.
What are the moons of Jupiter like? Would they look like “up close”?

The 1968 movie “2001 A Space Odyssey” has them similar and looking like our Moon.
All of them together (sibling portrait)

Images scaled to give correct relative sizes
Exploring Europa

What is under its ice-covered plains?
Europa is slightly smaller and less massive than our Moon. It is of interest because the entire moon is encased in ice. There are cracks and other features that hint at liquid water at some point below the surface,
Views of the cracks from Galileo

Picture about 100 miles on a side
A related phenomenon. The ice rafts of Europa

Similar features seen in arctic ocean and are due to flows of ocean underneath
Evidence for flows from beneath the surface of Europa
There is evidence (circumstantial) for liquid water under the surface, but how far down is it? What is below the water?

Spacecraft missions to Europa over the next few decades might tell us
Speculations on interior structure of Europa
A summary of what we know about Europa

• Slightly smaller in mass and diameter than the Moon
• Surface covered with water ice casing
• Evidence for surface “activity” from cracks and grooves, and ice rafts
• Small numbers of craters implies surface has reformed in last 100 million years
• Estimates that liquid layer, “sealed ocean” is between 10 - 50 kilometers below the surface, with possible rocky sea floor
A future Europa Lander could tell us much about the possible subsurface ocean of Europa
Further out...to the edge of the Solar System
Uranus and Neptune... where are they? Let’s look at a Table!

<table>
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<tr>
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<th>P(yr)</th>
<th>ecc</th>
<th>Incl (degrees)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Uranus</td>
<td>19.20</td>
<td>83.7</td>
<td>0.046</td>
<td>0.8</td>
</tr>
<tr>
<td>Neptune</td>
<td>30.5</td>
<td>163.7</td>
<td>0.011</td>
<td>1.8</td>
</tr>
</tbody>
</table>


What do they look like?
Our best views (and scientific information) come from visits (flybys) of the Voyager 2 spacecraft.
Uranus as seen by Voyager 2
Neptune as seen by Voyager 2

They look like “blue Jupiters”
How do they match up to Jupiter and Saturn?

Smaller than Jupiter and Saturn; much bigger than the Earth
Uranus (and Neptune) substantially larger than Earth
Uranus and Neptune (just the facts, Ma’am)

<table>
<thead>
<tr>
<th>planet</th>
<th>D (rel to Earth)</th>
<th>M (rel to Earth)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Uranus</td>
<td>4.01</td>
<td>14.5</td>
</tr>
<tr>
<td>Neptune</td>
<td>3.88</td>
<td>17.1</td>
</tr>
</tbody>
</table>

Uranus and Neptune are relevant in the exoplanet context
How do we summarize all of this?

• The small rock planets are in close to the Sun
• The big, gaseous planets are way out, far from the Sun
• Mars *may have* had habitable conditions on its surface billions of years ago
• Moons of the outer planets (Europa, Titan) may be promising locations for life