ANNOUNCEMENTS:

• CLASS WEBSITE UP AND RUNNING @ http://casaweb.colorado.edu/astr2000/

• THURSDAY’S LECTURE AT FISKE will be on Polynesian Navigation

• OFFICE HOURS: STOCKE: WED 1:30—2:30 AT Pekoe’s Coffee Shop in ATLAS or by appointment (2-1521). HW Club starts tomorrow at 11-1 and 4-6pm in D142 Duane Physics.

• FIRST HOMEWORK HANDOUT THIS THURSDAY; DUE FOLLOWING THURSDAY. THIS ONE WEEK CADENCE FOR HOMEWORKS WILL CONTINUE EVERY OTHER WEEK THROUGHOUT THE TERM

• OPTIONAL OBSERVING SESSION THIS COMING THURSDAY NIGHT AT SOMMERS-Bausch Observatory (small dome up hill from Fiske) 8:30-10pm
Up for Discussion

1. DIURNAL (DAILY) MOTION OF THE SKY (REDUX):

2. MOTIONS OF SKY AT DIFFERENT LATITUDES

3. THE “STAR COMPASS”

4. (SOME) SECRETS OF POLYNESIAN NAVIGATION (MORE on THURS)
What constellations would be visible in the sky after Sunset this day?

10. If you could see stars during the day, this is what the sky would look like at noon on a given day. The Sun is near the stars of the constellation Gemini. Near which constellation would you expect the Sun to be located at sunset?

A. Leo  
B. Cancer  
C. Gemini  
D. Taurus  
E. Pisces
What constellations would be visible in the sky before Sunrise this day?

10. If you could see stars during the day, this is what the sky would look like at noon on a given day. The Sun is near the stars of the constellation Gemini. Near which constellation would you expect the Sun to be located at sunset?

A. Leo
B. Cancer
C. Gemini
D. Taurus
E. Pisces
FOR ANCIENT HUMANS THE MOTIONS VISIBLE IN THE SKY DEFINED THE VERY NATURE OF TIME AND INCREMENTS OF TIME


- **THE DAY IS THE TIME BETWEEN SUCCESSIVE NOONS**.

- **AT NIGHT THERE WERE THE **Decans**. Star groups that define the nighttime hours by their successive risings, one after another**.

- **The tradition of the 24 hour day probably came from ancient Egypt but no one knows for sure**.
One decan “constellation” is marked in a green box and “marches” across the 70 day calendar diagonally as it rises earlier and earlier each 10 days.

ONE NEW DECAN EVERY 10 DAYS → 36 DECANS IN TOTAL

NOTE: Big Dipper (“Bull’s Thigh” constellation at top !)
The Celestial Sphere

DAILY MOTION OF THE SKY: GREEN LINE IS THE CELESTIAL EQUATOR WHEREON STARS RISE DUE EAST AND SET DUE WEST
DAILY MOTION OF THE SKY: GREEN LINE IS THE CELESTIAL EQUATOR WHEREON STARS RISE DUE EAST AND SET DUE WEST
ONE HOUR LATER, A NEW DEACAN IS ON THE EASTERN HORIZON

THE CELESTIAL SPHERE

General properties of the sky
Hartmann/The Cosmic Journey, 4th ed., Fig. 1-3; The Cosmic Voyage, Fig. 1-3

DAILY MOTION OF THE SKY: GREEN LINE IS THE CELESTIAL EQUATOR WHEREON STARS RISE DUE EAST AND SET DUE WEST
2 HOURS LATER...ANOTHER DECAN APPEARS IN THE EAST

General properties of the sky
Hartmann/The Cosmic Journey, 4th ed., Fig. 1-3; The Cosmic Voyage, Fig. 1-3

THE CELESTIAL SPHERE

DAILY MOTION OF THE SKY: GREEN LINE IS THE CELESTIAL EQUATOR WHEREON STARS RISE DUE EAST AND SET DUE WEST
The meridian is where stars reach their highest locations of the night.

**Daily Motion of the Sky.** The *meridian* is where stars reach their highest locations of the night.

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*General properties of the sky*

Hartmann/The Cosmic Journey, 4th ed., Fig. 1-3; The Cosmic Voyage, Fig. 1-3
HOW ANCIENT PEOPLE ALIGNED THEIR STRUCTURES AND TO COME INTO ORIENTATION WITH THE COSMOS

PYRAMIDS AT GIZA ALIGNED TO TRUE NORTH-SOUTH & SO WITH ORION (OSIRIS) CROSSING THE MERIDIAN
ANCIENT COSMOLOGY HAS THREE LEVELS: HEAVENS ABOVE, REALM OF GODS; UNDERWORLD BELOW, REALM OF DEATH AND TRANSFORMATION, AND, IN BETWEEN THE FLAT PLATE OF THE EARTH’S SURFACE. SHAMANS = SPIRITUAL LEADERS WHO COULD MOVE BETWEEN THESE LEVELS.

EARTH WAS SEEN AS IMMOBILE AT THE CENTER OF ALL CREATION. EARTH’S SURFACE WAS BY FAR THE LARGEST THING IN CREATION.

ANY MOTIONS IN THE SKY ARE DUE TO THE OBJECTS IN THE SKY, NOT THE EARTH. DIURNAL OR DAILY MOTION OF SUN, MOON, PLANETS AND STARS and LONGER MOTIONS OF SUN, MOON & PLANETS THROUGH THE STARS.

IS THE WORLD (UNIVERSE) FINITE OR INFINITE? MOSTLY NOT AN ISSUE FOR THE ANCIENTS.
THREE LEVEL COSMOLOGY OF THE ANCIENTS

Ancient Hebrew Conception of the Universe

The ancient Hebrews divided the world into Heaven, Earth, Sea, and the Underworld.

1. **Heaven of Heavens**
   - Heaven of Fire (Heaven of Fire for Greeks and others)
   - Firmament with the Stars

2. **Ocean of Heaven**
   - Firmament
   - Pillars of Heaven

3. **Earth**
   - Primeval Ocean
   - Underworld
   - Sheol
   - Foundations of the Heavens

4. **Waters Above the Firmament**
   - Waters
   - Sun
   - Moon

5. **The Great Deep**
   - Sea
   - Mountains

The ancient Hebrews viewed the sky as a vault divided into two parts: Heaven of Heavens and Ocean of Heaven. The Earth was considered to be the center of the universe, with the heavens above and the underworld below. The Underworld was a place of eternal rest and was often depicted as a dark, shadowy realm.

This cosmology reflects the ancient belief in a hierarchical universe with distinct realms for the divine, human, and the dead.
NEWGRANGE IRELAND: A c. 3000 BCE “PASSAGE TOMB”. ALIGNED WITH THE MID-WINTER SUNRISE …TO CONNECT THE UNDERWORLD AND SKY REALMS
UNITS OF TIME CREATED UNITS OF ANGLE IN THE SKY:

- C. 2000 BCE BABYLONIAN CALENDAR HAD 360 DAYS with TWELVE 30 DAY MONTHS
- 360 DEGREES IN A FULL CIRCLE MEANS SUN MOVES 1 DEGREE THROUGH STARS PER DAY
- BABYLONIAN NUMBERS WERE BASE 60 so degrees divided into 60 ARC-MINUTES and 1 arc-minute divided into 60 ARC-SECONDS (just like minutes and seconds of time)
- Eye’s resolution ~ 1 arc-minute
- Good telescope’s resolution ~ 1 arc-second

HORIZON TO ZENITH = 90 ° (CALLED ALTITUDE)

FULL CIRCUMFERENCE OF HORIZON = 360° (CALLED AZIMUTH)

BASE 60 COMES FROM BABYLONIANS
360 degrees around full horizon & along ANY GREAT CIRCLE around the sky.
90 degrees from horizon to zenith.
HORIZON SYSTEM: IS A LOCAL SYSTEM OF Azimuths and Altitudes

CELESTIAL SYSTEM: IS A GLOBAL SYSTEM OF LATITUDES & LONGITUDES

THE CELESTIAL SPHERE
HORIZON SYSTEM:

- **ALTITUDE** = ANGLE UP FROM HORIZON (0 TO 90°)
- **AZIMUTH** = ANGLE FROM DUE NORTH THROUGH EAST (0 TO 360°)

CELESTIAL SYSTEM IS THE EXTENSION OF THE TERRESTRIAL LATITUDE/LONGITUDE SYSTEM ONTO THE SKY:

- **DECLINATION** = CELESTIAL LATITUDE (aka: DEC)
- **RIGHT ASCENSION** (aka RA) = CELESTIAL LONGITUDE (WILL NOT BE USED MUCH)
**HERE AT BOULDER:**

<table>
<thead>
<tr>
<th>LOCATION</th>
<th>DEC</th>
<th>ALTITUDE</th>
</tr>
</thead>
<tbody>
<tr>
<td>ZENITH</td>
<td>40°</td>
<td>90°</td>
</tr>
<tr>
<td>NCP</td>
<td>90°</td>
<td>40°</td>
</tr>
<tr>
<td>CE</td>
<td>0°</td>
<td>50°</td>
</tr>
<tr>
<td>SIRIUS</td>
<td>-17°</td>
<td>33°</td>
</tr>
<tr>
<td>VEGA</td>
<td>39.5°</td>
<td>89.5°</td>
</tr>
<tr>
<td>PLEIADES</td>
<td>24°</td>
<td>76°</td>
</tr>
<tr>
<td>POLARIS</td>
<td>89.5°</td>
<td>40°</td>
</tr>
</tbody>
</table>

**Along the Meridian:**
- **Zenith:** 70° North
- **Celestial Equator:** Declination = Local Latitude
- **NCP (North Celestial Pole):** Declination = 90°
- **Altitude of NCP:** Local Latitude
- **Celestial Equator:** Declination = 0°

*At Zenith: Declination = Local Latitude (40° north here in Boulder)*

*North Celestial Pole (NCP) has Declination = 90°*

*Altitude of NCP = Local Latitude*

*Celestial Equator has Declination = 0°*

*At northern latitudes the NCP never sets*
The daily motion of any and all objects (including the sun) carries them across the sky from rising to setting so that they “culminate”, attain their highest altitude in the sky when they cross the meridian, the local North-South line across the sky.

Along the meridian is the only location where altitude of star has simple meaning for celestial navigation.
INTRODUCING THE “MERIDIAN SLICE”

A SLICE THROUGH THE CELESTIAL SPHERE FROM DUE NORTH TO DUE SOUTH THROUGH THE ZENITH… which means long the MERIDIAN !!

NCP IS ON THE MERIDIAN AND APPEARS ON THE SLICE

CELESTIAL EQUATOR CROSSES THE MERIDIAN AND SO THERE IS A POINT FOR IT ON THE SLICE TOO

THREE EXAMPLES AT DIFFERENT LATITUDES:

1. **At Boulder**
   - $\theta = 48^\circ$ Dec
   - C.E. (Celestial Equator)

2. **At Key West**
   - $\theta = 25^\circ$ Dec
   - C.E. (25° N Latitude)

3. **At Equator**
   - $\theta = 0^\circ$ Dec
   - C.E. (Celestial Equator)

*Notice: As latitude changes, zenith changes Dec. Celestial sphere pivots N-S.*
OK, LET’S GET QUANTITATIVE (TO KEEP FROM GETTING LOST). LOCATION = BOULDER (40° LATITUDE).

ORION’S BELT IS ON THE CELESTIAL EQUATOR (CELESTIAL LATITUDE = 0°). So, how high (altitude angle) does Orion’s Belt get when it crosses the meridian (its highest point in the sky)?

A. IT GOES THROUGH THE ZENITH ➔ ALTITUDE = 90°

B. IT SKIRTS THE HORIZON ➔ ALTITUDE = 0°.

C. BOULDER IS AT 40° LATITUDE ➔ ALTITUDE = 40° WHEN IT CROSSES THE MERIDIAN

D. BOULDER IS AT 40° LATITUDE ➔ ANGLE DOWN FROM ZENITH = 40° WHEN BELT STARS CROSS THE MERIDIAN ➔ MAXIMUM ALTITUDE OF ORION’S BELT = 90° - 40° = 50°
GIVEN THIS EXAMPLE, IF A LONG DISTANCE OCEAN NAVIGATOR WANTED TO KEEP TRACK OF THEIR LATITUDE, THEY COULD MEASURE THE ANGLE FROM THE HORIZON UP TO A SPECIFIC SET OF STARS.

STARTING AT THE LATITUDE of BOULDER, IF THE BOAT WAS SAILING towards the EQUATOR, ORION’S BELT WOULD: ASCEND OR DESCEND?
Latitude determined by altitude of stars as they cross the meridian (i.e., at their highest point above the horizon)

Using your hand and fingers as a measuring device to determine the altitude of stars close to the horizon can be accurate to a fraction of a degree of latitude. (One degree = 67 miles). Someone adept at this method can determine their latitude within 10—20 miles. Modern traditional Hawaiian navigators now use entire “Star Lines” to determine their latitude.
ACRUX and GACRUX are a “Meridian Pair” in the long axis of *Cared-for by the Moon (Southern Cross)*.

When the *Southern Cross* stands vertically it marks due South!
Concept of **meridian pairs** allows navigator to know when the stars are along the meridian and so can be used to determine latitude.

Southern Cross VERY high in sky at Tahiti, slowly moves down in the sky as the boat sails north and when the boat reaches the latitude of Hawaii:

The lowest star in the Cross is the same angle off the horizon as the two vertical stars are apart.
QUESTION: thinking about the rising and setting of stars, are there any stars which rise and set at exactly the same location at any time of year?

a. NONE. All stars rise and set at different locations night to night.

b. ALL. All stars rise and set at specific positions along the horizon. These specific positions are set and do not change during the year.

c. NONE. While all stars rise and set at specific set positions, these locations shift back and forth with the seasons.

d. POLARIS, the North Pole Star, always rises and sets due north.

e. ORION’S BELT stars and other stars on the Celestial Equator always rise due east and set due west.

f. VEGA and other stars that go directly overhead here in Boulder, always rise due east and set due west.
THE RISING AND SETTING POINTS OF ALL STARS IS SYMMETRICAL AROUND THE MERIDIAN (NOT 180° OPPOSITE).

THIS IS ALSO TRUE FOR THE SUN, MOON AND PLANETS ON ANY GIVEN SINGLE DAY.

THESE RISING AND SETTING AZIMUTHS ARE FIXED AT ANY SPECIFIC LATITUDE.

> POLYNESIAN NAVIGATORS MEMORIZE APPROX. RISING BEARINGS OF STARS

⇒ SETTING BEARINGS ARE THEN SYMMETRICAL AROUND N-S LINE (THE "MERIDIAN")
WHAT STAR DO YOU FOLLOW TO GET FROM KAILUA/KONA TO HONOLULU?
AT ANY GIVEN LATITUDE THE STARS, SUN AND MOON RISE AND SET AT AN ANGLE OFF THE VERTICAL EQUAL TO THE LATITUDE:

e.g., stars rise and set vertically at the equator;

At 40 degrees off the vertical here in Boulder; and

At the North and South Poles the stars move entirely horizontally and so never rise or never set depending on their celestial latitude.
Near the Equator where Polynesians navigated, the stars, sun and moon move nearly vertically up and down in the sky and so...

They stay on the same “bearing” (azimuth) and so give a nearly constant heading as they rise or set.
SECRETS of TRADITIONAL POLYNESIAN NAVIGATION

VOYAGING CANOE "HOKULE'A" UNDERWAY OFF HAWAII
THE POLYNESIAN TRIANGLE:
10 Million square miles of Ocean
Samoa, Fiji & Tonga in near Polynesia settled by circa 1000 BCE
Rarotonga and Tahiti at the Center (circa 500 BCE)
Hawaii to the North (circa 500 CE)
Rapa Nui (Easter Island) to the East (circa 500 CE)
Aeoterora (New Zealand) to the South and West (circa 800 CE)
The Polynesian Voyaging Society (founded in 1973 by Ben Finney, Tommy Holmes and Herb Kane’) built the voyaging canoe Hokule’a but no one knew how to navigate by traditional methods….until Ben found Pius Mao Piallug of Satawal in Micronesia who was taught by his grandfather. He was flown to Hawaii to navigate Hokule’a to Tahiti and back even though he had never been more than 500 miles from his home island…and he did it!
Latitude determined by altitude of stars as they cross the meridian (i.e., at their highest point above the horizon)

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ACCURACY OF OBSERVATIONS:

- LATITUDE: 1 DEGREE = 67 MILES
  \[ \frac{24,000 \text{ MILES}}{360 \text{ DEGREE}} = \text{MILES Per Degree} \]

IF a Traditional Navigator can determine the height of the Southern Cross to ½ pinky finger width = ½ degree then she knows her **latitude** to 33 miles.

- LONGITUDE: Since stars change their east-west location with time, **longitude cannot be known without a clock**!

- Star could be higher in the sky either because
  1. It is spotted at a **later time**
  2. You spot it from a location **farther east** than you think!

THE PROBLEM OF LONGITUDE

A **CLOCK** IS NEEDED ALONG WITH AN OBSERVATION OF A HEAVENLY BODY (STAR OR SUN TRADITIONALLY) TO DETERMINE LONGITUDE!
Celestial Navigation can allow you to determine LATITUDE BUT NOT LONGITUDE.

Celestial Navigation can get you close…. Best accuracy of measuring altitudes $\approx \frac{1}{2}$ degree $\rightarrow$ 33 miles.

But at 33 miles away you can still not see a low lying island or atoll. $\rightarrow$ Even if you get close you can still miss.

How did Traditional Polynesian Navigators navigate without knowing their LONGITUDE and when they got close how did they make landfall?

The Secrets….on Thursday at Fiske!
Nuku Hiva to Hawaii: 2500 miles of open ocean

“Sail North until you see the star that never sets. Then turn downwind and allow the Star of Gladness (Hokule’a) to go directly overhead every night”
ACRUX and GACRUX are a “Meridian Pair” in the long axis of *Cared-for by the Moon (Southern Cross)*.

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