Astronomical Coordinates

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Contents

Introduction

- Exploring the Universe → Need for a coordinate system
- But everything is moving → Complicated situation
  - Earth spins around its axis
  - Influence of Sun, Moon, Planets → Earth axis subjected to precession
  - Earth axis also subjected to nutation
  - Earth rotates around the Sun
  - Sun rotates around the center of our Galaxy
  - Our Galaxy moves through space within the local cluster
- What should we take as origin and orientation of the axes ?

* Use different coordinate systems depending on what one wants to observe

Okido, we are used to that (e.g. Cartesian, Spherical, Comoving, ...)

- Due to the movements we need also a time system

Effects of the above movements are observed on very different timescales

* Use different time systems depending on what one wants to observe

Not always practical (a lab with many clocks) → Overall time ?

Time systems

Solar Time

- Elapsed time between two identical observed positions of the Sun
  Basis of our usual 24 hour day/night system
- Definition : 1 day = 24 hours   1 hour = 60 min.   1 minute = 60 sec.
  Time definition : 12:00h when the Sun is at the observer's meridian
- Different locations have different values of the Local Time (LT)
  Definition : Greenwich is defined as origin at the 0° meridian

$\ast$ Time rate varies (eccentricity of Earth's orbit and tilt of Earth's spin axis)

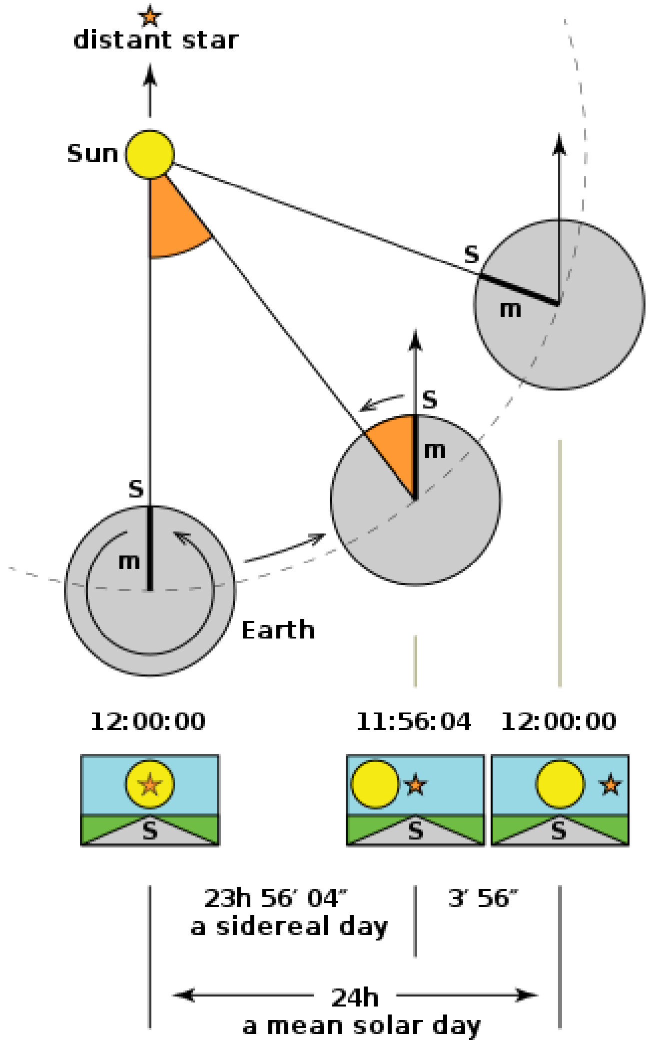
- Use the mean rate which averages out these effects $\rightarrow$ Mean Solar Time
- So at each location we have two times
  - Steady clock with noons 24 hours apart $\rightarrow$ Local Mean Time (LMT)
  - Actual position of the Sun $\rightarrow$ Local Apparent Time (LAT)
- The difference between LAT and LMT is called the Equation of Time

$\ast$ The reference is the Greenwich Time (GMT or GAT)

Sidereal Time

- Elapsed time between two identical observed positions of the same Star
  Closely related to Solar Time but not identical
- Observer outside the Solar system :
  The Earth spins around its axis in 1 "day"
  The Earth rotates around the Sun in n "days"
  After 1 Solar orbit the Earth has made 1 extra revolution around its spin axis
  $\rightarrow$ 1 sidereal day $= (1 - 1/n)$ solar day
- Consequently : 1 sidereal day = 23h 56m 04.09s (Mean Solar Time)
  Time definition : Related to the coord. of a Star at the observer's meridian
  - These coordinates will be explained later
  - These coord. vary due to precession and nutation of the Earth's spin axis

Sidereal time versus Solar time



Time systems

- Precession effect is stable and well known, nutation effect is more complex

  Precession period : 25770 years
- Use average epoch (50 years) coordinates to correct for the precession effect

  $\rightarrow$ Mean Sidereal Time
- So at each location we have two times
  - Local Mean Sidereal Time (LMST) (i.e. precession included, nutation not)
  - Local Apparent Sidereal Time (LAST) (incl. both precession and nutation)

$*$ The reference is the Greenwich Sidereal Time (GMST or GAST)

- This looks all fine, but what determines the value of the time intervals ?

  In other words : What counts the elapsed number of seconds ?

International Atomic Time (TAI)

- The absolute value of the second is defined by atomic transitions
  Remember that we used ${}^{12}_{6}$C to define the atomic mass unit (amu)
- ${}^{133}_{55}$Cs has a hyperfine $4 \rightarrow 3$ transition of the ${}^{2}S$ ground state
  This transition happens very frequently and at a very stable rate
  1 atomic (SI) sec. $\equiv$ 9192631770 cycles of this ${}^{133}_{55}$Cs transition
- An individual Cs clock has a stability of the order of 10^{-14} per day
  Using a set of Cs clocks all over the world provides even better stability

$*$ Basis of TAI : Temps Atomique International

- TAI : Stable time system but not linked with astronomical phenomena
  TAI was introduced (= start epoch) 01-jan-1958 00:00:00 GAT
  $\rightarrow$ The reference for the absolute TAI time is Greenwich
  Earth's spin is irregular $\rightarrow$ Alternative for TAI needed

Coordinated Universal Time (UTC)

- **Astronomical time standard : UTC (Temps Universel Coordonné)**
  UTC transpires at the same rate as TAI $\rightarrow$ Clock ticks every SI second
  Average correction for the irregular Earth spin by introducing leap seconds

∗ **The leap second correction was introduced on 01-jan-1972 00:00:00 GAT**
  This empirical correction is needed only every few years
  See `http://maia.usno.navy.mil/ser7/tai-utc.dat` **for an overview**

- **This implies : TAI-UTC=ΔAT   Currently (2019) ΔAT=37 sec.**

∗ **UTC is broadcast via various servers using a Network Time Protocol (NTP)**
  See for instance `http://www.time.gov` **or** `http://www.time.gov/widget.html`

∗ **The reference for the absolute UTC time is Greenwich**
  UTC is not updated for Daylight Saving Time (DST)

- **GPS timing was started at 06-jan-1980 00:00:00 UTC with ΔAT=19 sec.**
  GPS clocks tick at the same rate as TAI $\rightarrow$ GPS=TAI-19 sec. (fixed)

Time systems

Universal Time (UT1)

- Time corrected for the actual Earth spin is called **Universal Time (UT1)**
  This implies : **UT1-UTC=ΔUT1**
  See `https://hpiers.obspm.fr/iers/series/opa/eopc04` for daily updates

$*$ $|\Delta$UT1$|$ is kept < 0.9 sec. by introduction of leap seconds in UTC

Terrestrial Time (TT)

- This is the TAI time corrected for GR effects at average sea level
  Started at 01-jan-1977 00:00:00 TAI with **TT $\equiv$ TAI+32.184 sec.**
  This makes TT a continuation of the predecessor Ephemeris Time (ET)

Geocentric Coordinate Time (TCG)

- The same as TT but for a reference frame not in the Earth's grav. potential
  Relation : **TCG $\approx$ TT+$7 \cdot 10^{-10}\Delta$T**
  $\Delta T \equiv$ elapsed time in SI sec. since 01-jan-1997 00:00:00 TT

Julian Date (JD)

- Comparison of observations over many years is quite cumbersome
  - Varying number of days in a year (leap years) and in various months
  - The absolute time indication is position dependent
  - Some sort of correction may have been applied at some time
- Can't we have a steady ticking clock yielding an overall absolute reference ?

  Yes we can !
- A continuous day counting system has been introduced called Julian Dates

  Origin JD=0 has been defined as 01-jan-4713 BC at 12:00:00 Greenwich

  Each Julian day has exactly 86400 seconds

  No leap seconds are introduced

  Each Julian century has 36525 days $\rightarrow$ Each Julian year has 365.25 days
- Example : 02-jan-2000 12:00:00 UT corresponds to JD=2451546.0

$*$ This day counting system can be used with any time system at Greenwich

Modified Julian Date (MJD)

- To avoid too large numbers a **Modified Julian Date** has been introduced
  Same definitions as for the Julian Date but different origin

∗ **Origin MJD=0** has been defined as **17-nov-1858 at 00:00:00 Greenwich**
  Consequently : **MJD=JD-2400000.5**

- In practice MJD is used for calculations (computer accuracy), plots etc.

Julian Epoch (JE)

- JE = fractional elapsed Julian year count since 01-jan-0000 12:00:00
  Example : 01-jan-1965 12:00:00 UT corresponds to JE=1965.0

Besselian Epoch (BE)

- BE = fractional elapsed Besselian year count since 01-jan-0000 12:00:00
  A Besselian (tropical) year is defined to be 365.242198781 days

Coordinate systems

- Celestial positions : Convenient to use spherical coordinates (r, θ, ϕ)

  In indicating a direction, the distance doesn't matter $\rightarrow$ Ignore r
- Celestial positions are indicated by two angles called latitude and longitude

  But w.r.t. to which origin are these angles provided ?

* Define an equator by taking a so called great circle

  Great circle : Centered at the sphere center and encompasses the full sphere
- The equator indicates the zero of latitude

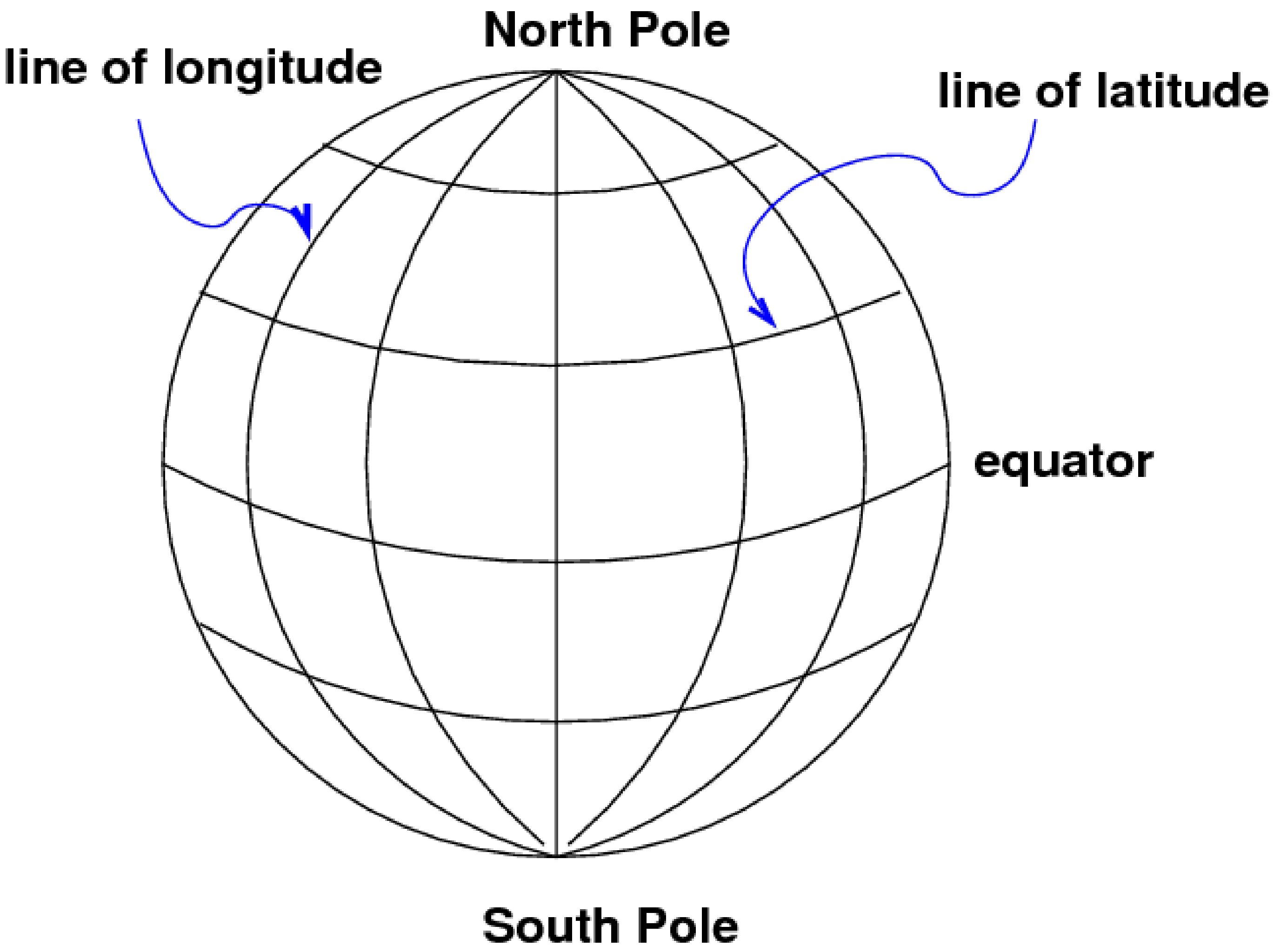
* Choose a location on the equator as zero for the longitude

  Define the directions of positive and negative latitude and longitude

  The lines of constant longitude are called meridians
- Reference systems like this are called celestial reference systems

  It is obvious that there are many different possibilities for such a system

A generic celestial reference system



Horizon coordinates

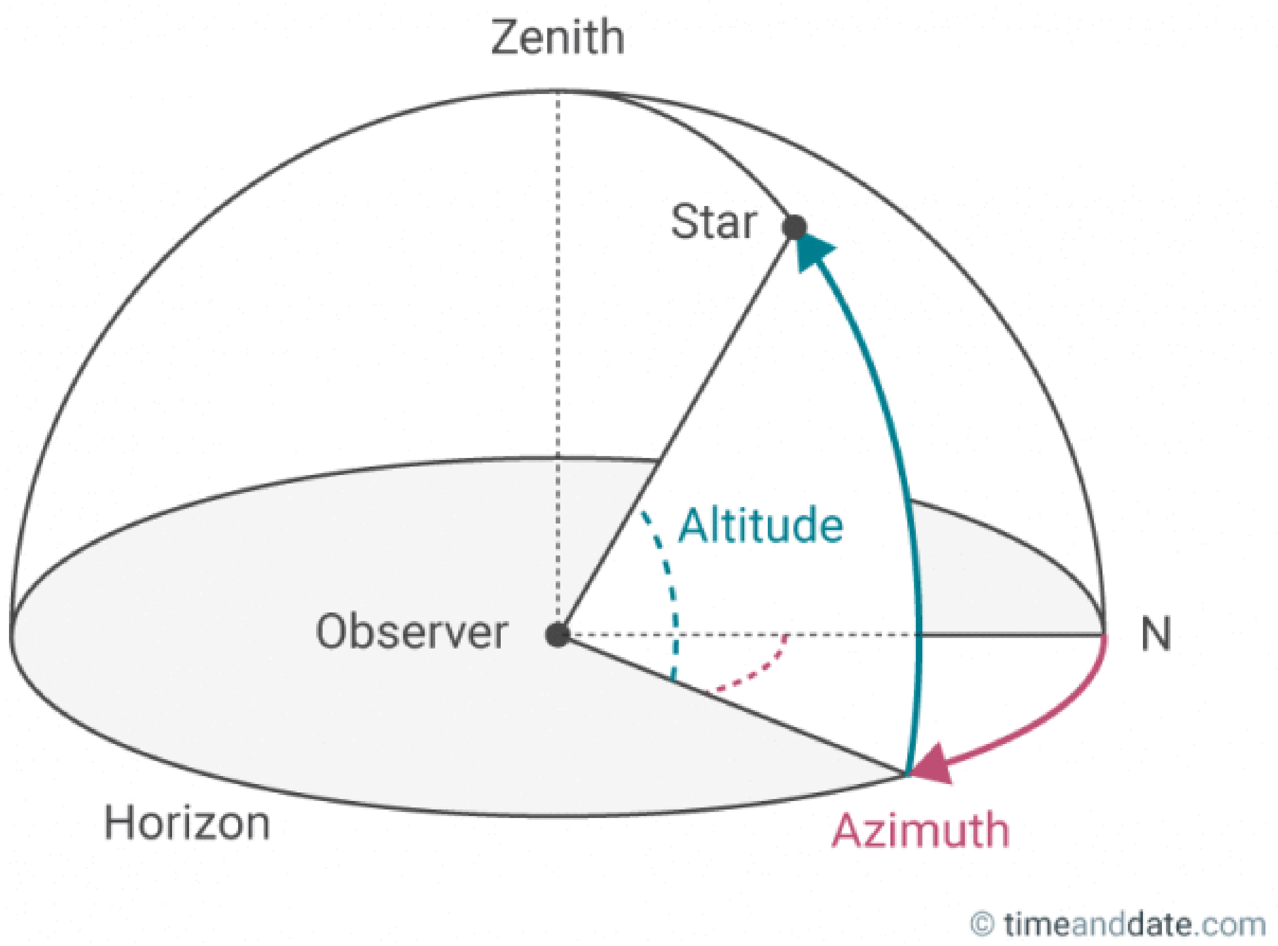
- Imagine standing at night in an open field without any houses, trees etc.
  You feel as if you are the centre of everything
- Conventions to define the observer centered reference system
  The point straight above is called Zenith and straight below is called Nadir

∗ Take the horizon as equator
  The (latitude) angle above the horizon of a star's position is called Altitude
  Alternatively the angle w.r.t. the Zenith (Zenith angle) of a star can be given

∗ Take the North point on the equator as zero longitude
  The (longitude) angle measured eastwards to a star's position is called Azimuth

∗ Notes :
  For an observer at a Pole, Greenwich defines the zero longitude
  Values of altitude and azimuth depend on the location of the observer
  Values of altitude and azimuth change fast due to the Earth's spin

The horizon coordinate system



Equatorial coordinates

- Imagine standing on one of the Poles at the Earth's spin axis
  With time the azimuth of a star will change, but not its altitude
  This is quite convenient if one wants to follow a certain object

$*$ Due to the coincidence of the Zenith-Nadir axis with the Earth's spin axis
  $\rightarrow$ Your equator coincides with the Earth's equator

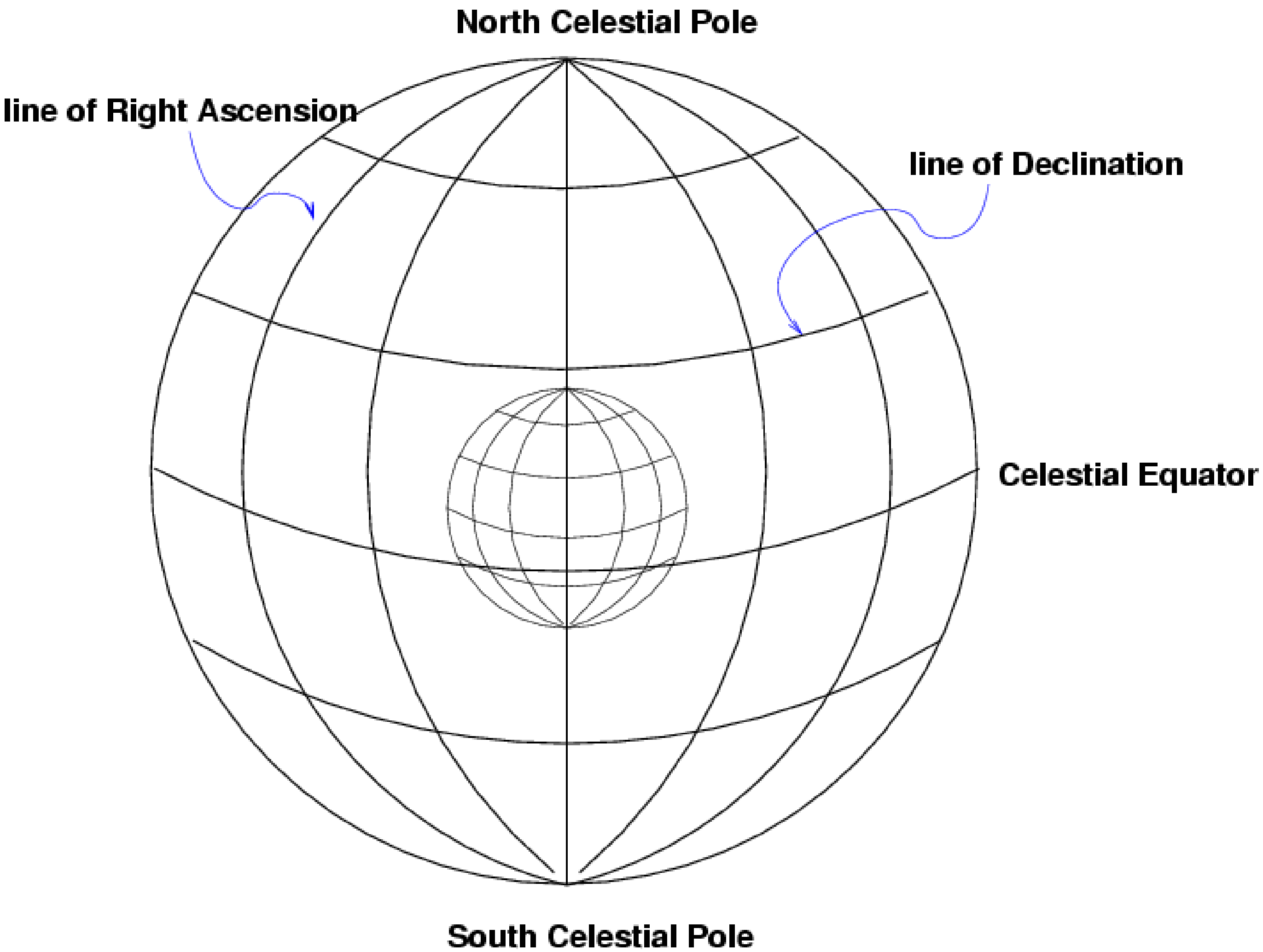
- Conventions to define the equatorial celestial reference system

$*$ Take the center of the Earth as the center of the reference system

$*$ Take the (projection of) the Earth equator as equator
  This projection is called the celestial equator
  The angle above the equator of a star's position is called Declination
  The angle of longitude is called Right Ascension

- What to take as zero longitude ?
  Preferably a point that doesn't change with time.

The equatorial celestial reference system



Coordinate systems

- The Earth rotates around the Sun in a fixed plane

  The Earth's spin axis is inclined ($\sim 23.4^\circ$) with the normal to this plane
- Imagine that the Earth only rotates around the Sun; no spin around its axis

  Consider the Earth as a perfect sphere

  Observe from the Earth's center the position of the Sun over the year

  Project the Sun's trajectory on the Earth's surface

  $\rightarrow$ This projection is a great circle inclined ($\sim 23.4^\circ$) with the equator

  This projection of the Sun's trajectory is called the ecliptic
- The ecliptic will cross the equator twice per year

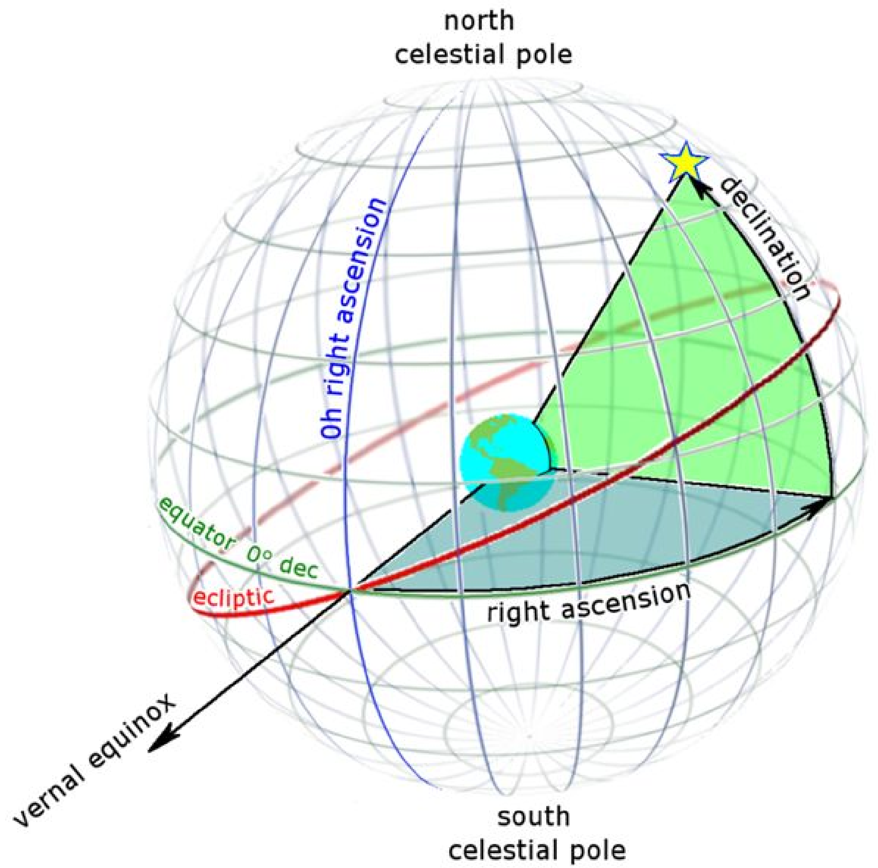
  Going from South to North in spring $\rightarrow$ Vernal equinox

  Going from North to South in autumn $\rightarrow$ Autumn equinox

$*$ Take the Vernal equinox on the equator as zero longitude

  The angle measured eastwards to a star's position is called Right Ascension

The equatorial coordinate system



Coordinate systems

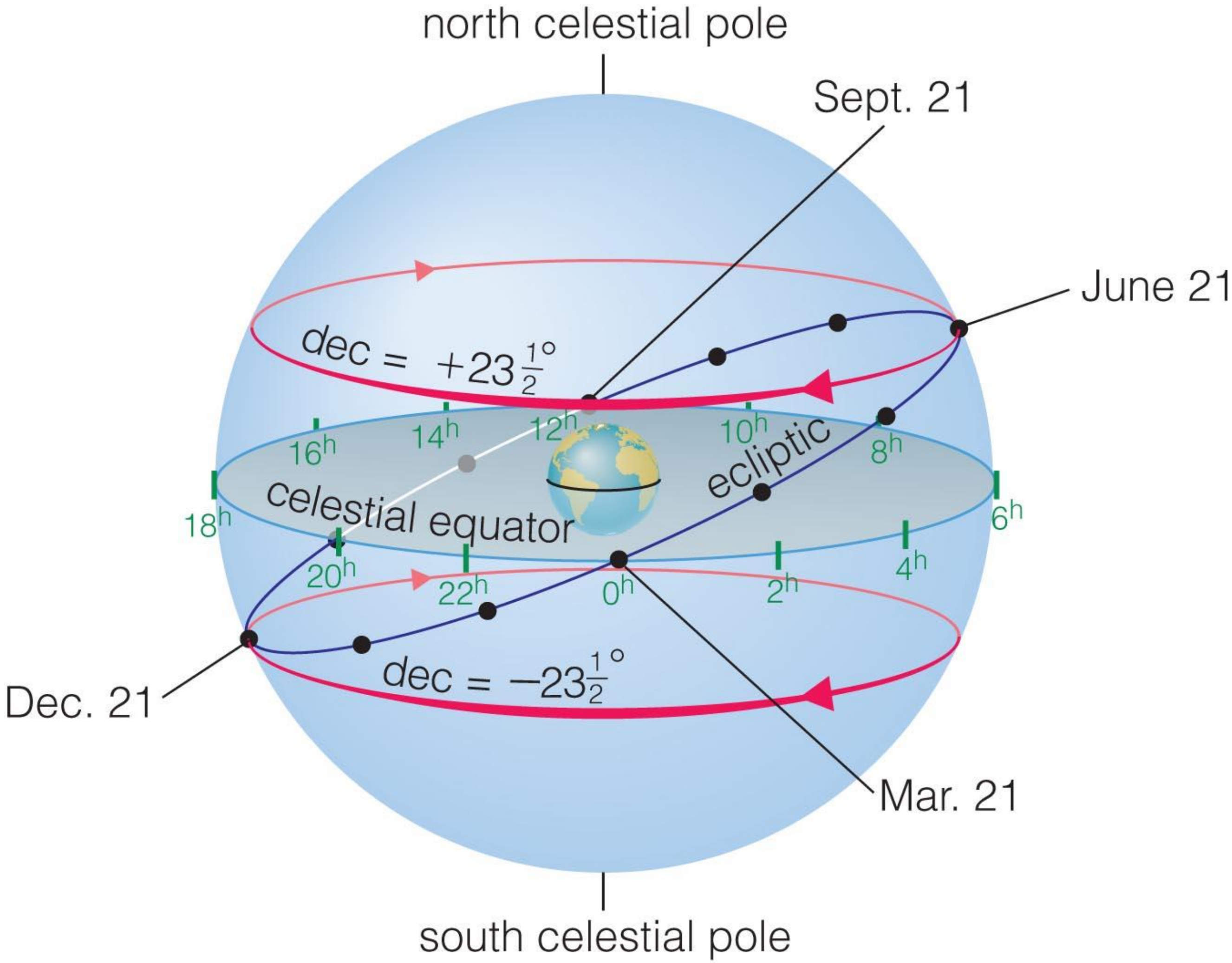
- Precession of the Earth's spin axis $\rightarrow$ Vernal equinox shifts along the equator
  One full turn (360°) in 25770 years $\rightarrow$ Quite a stable point
  Once every 50 years (epoch) the Vernal equinox position is updated
- The nutation of the Earth's spin axis induces also (minor) shifts in declinations

Notation conventions

- Declination (δ) is indicated in degrees (North +, South -)
- Right Ascension (α) is indicated in hours, minutes, seconds
  1 Full revolution (360°) in 24 hours $\rightarrow$ 1 hour $= 15^\circ$
- The average epoch coordinates we call Mean coordinates
  The Mean (α, δ) contain the precession correction, but not the nutation
- Including also the nutation correction we speak of True coordinates

$*$ So it is important to denote w.r.t. to which epoch origin the (α, δ) are given

Equatorial coordinate notations



Coordinate systems

- Example : The position of Sirius given in the 2 most recent epochs

  B1950 $\alpha = 06\text{h}\,42.9\text{m} \quad \delta = -16^\circ 39'$ (B stands for Besselian epoch)

  J2000 $\alpha = 06\text{h}\,45.1\text{m} \quad \delta = -16^\circ 43'$ (J stands for Julian epoch)
- The J2000 epoch is the standard for current astronomy

Sidereal Time

- We have seen that (α, δ) provide rather constant coordinates
- As the Earth spins around its axis, different stars will cross a certain meridian

* Sidereal Time $\equiv \alpha$ of the stars that cross the observer's meridian

- Since we can use the Mean and True coordinates we define

  LMST : Local Mean Sidereal Time

  LAST : Local Apparent Sidereal Time

  GMST : Greenwich Mean Sidereal Time

  GAST : Greenwich Apparent Sidereal Time

Hour Angle

- Hour Angle $\equiv$ The angular distance along the equator w.r.t. the meridian
- As before we define

  LMHA : Local Mean Hour Angle

  LAHA : Local Apparent Hour Angle

  GMHA : Greenwich Mean Hour Angle

  GAHA : Greenwich Apparent Hour Angle
- Since the Earth spins eastwards, stars in the east will cross the meridian later

  $\rightarrow$ Hour Angle is indicated (East +, West -)
- Example : Consider a star with $\alpha = 1\text{h}\,12\text{m}\,45.3\text{s}$ as True right ascension

  At 23:00:00 LAST this star is located $2\text{h}\,12\text{m}\,45.3\text{s}$ East of our meridian

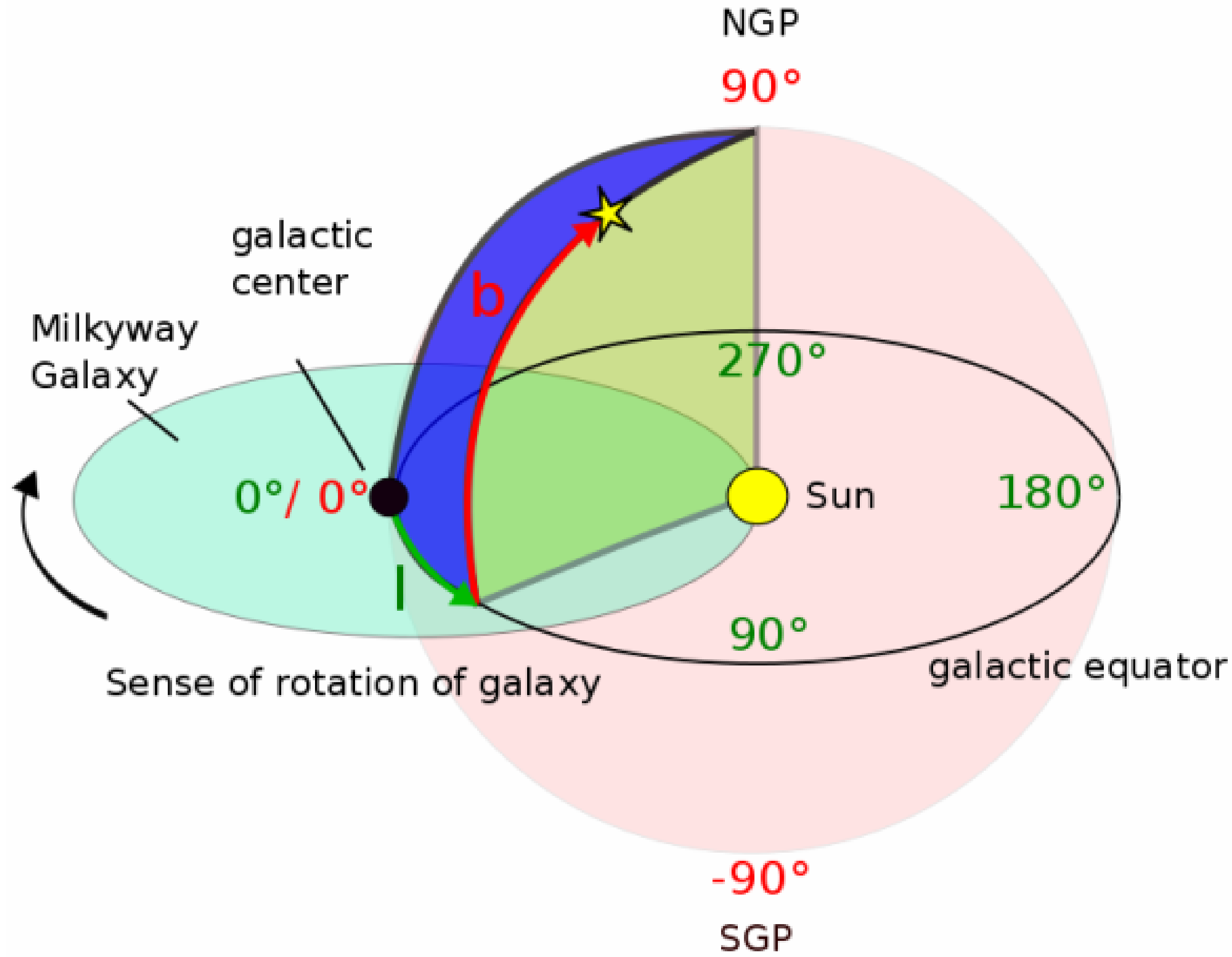
Galactic coordinates

- Sometimes it is instructive to locate objects w.r.t. the center our Galaxy
  In these cases it is convenient to use Galactic coordinates
- For Galactic coordinates the Sun is defined as center
  No effect of Earth spin or rotation around the Sun
- Take the great circle containing the Galactic Plane (GP) as equator
  $\longrightarrow$ Defines the North Galactic Pole (NGP) and South Galactic Pole (SGP)
- Take the direction of the Galactic Center (GC) as zero longitude

$*$ Galactic latitude b : degrees w.r.t. Galactic equator (North +, South -)

$*$ Galactic longitude l : degrees "eastwards" (like Right Ascension) from $l = 0$

The galactic coordinate system



Coordinate systems

- But there are some problems

  1. The Galactic Plane is not well defined (thickness of the disk)
  2. The position of the GC is not well known (extinction of light)

- Solution to 1 : Define the Galactic Plane by convention

$*$ Definition of North Galactic Pole (NGP) (based on observations):

$\alpha_{NGP} \equiv 12\text{h}\,49\text{m} \quad \delta \equiv 27^\circ\,24'$ (B1950)

$\rightarrow$ Celestial and Galactic equators are tilted by 62.6°

- Intersections of the Celestial and Galactic equators $\rightarrow$ None point to GC

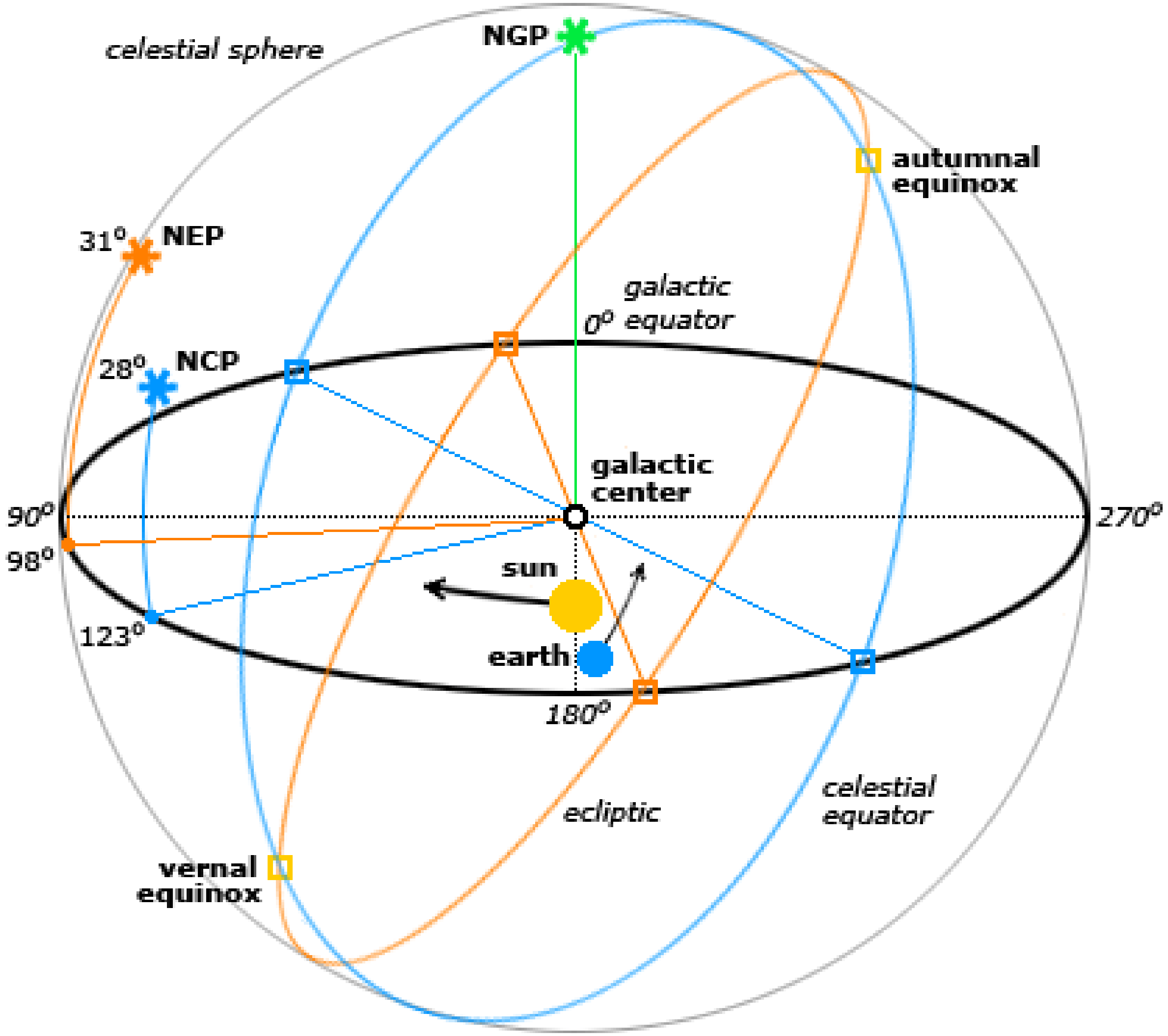
  $\rightarrow$ Define the Galactic long. of the North Celestial Pole (NCP) by convention

  Choose the convention such that the GC gets a gal. long. of about 0°

$*$ Galactic longitude of the North Celestial Pole (NCP) : $l_{NCP} \equiv 123^\circ$

Coordinate systems

The various celestial reference systems



Geocentric Ecliptic coordinates

- Convenient for locations w.r.t. the position of the Sun (e.g. planets, comets)
  Most planets move (more or less) in the ecliptic plane

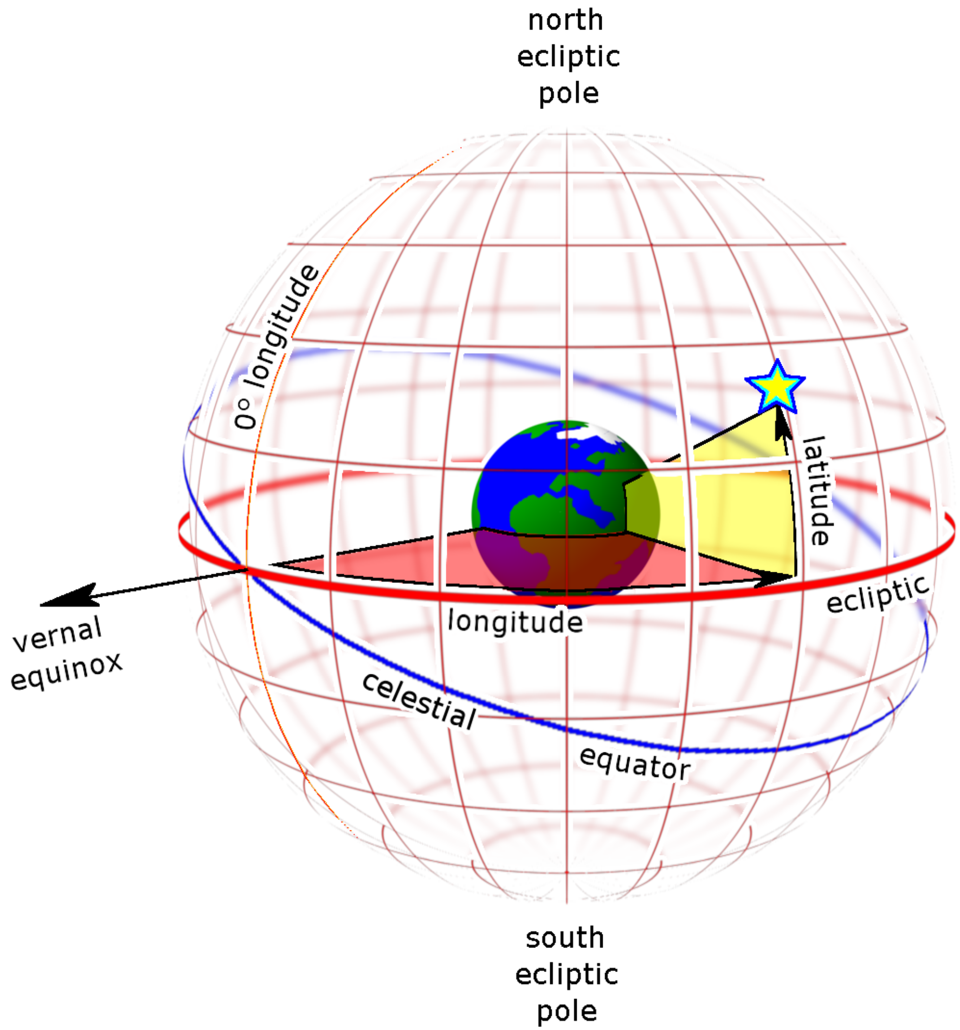
∗ Define the Earth as the center

∗ Take the ecliptic as equator

∗ Take the Vernal equinox as zero longitude

- Ecliptic latitude β : degrees w.r.t. the ecliptic (North +, South -)
- Ecliptic longitude λ : degrees eastwards from the Vernal equinox

The Geocentric ecliptic coordinate system



The International Celestial Reference System (ICRS)

- Recently (1989-1995) many very distant objects (quasars, AGN) were observed
  These objects are very far away $\rightarrow$ Movement of Earth or Sun doesn't matter
- Use these objects to define a fixed, time independent reference system

$*$ Take the average Celestial equator as equator

$*$ Take the average position of the Vernal equinox for zero longitude

ICRS latitude b : degrees w.r.t. the Celestial equator (North +, South -)

ICRS longitude l : degrees eastwards from the Vernal equinox

- ICRS coordinates match within 20 mas with the mean ones of the J2000.0

Transformations between the various systems

- Determine the various orientations at a certain time
- Just perform transformations via rotation matrices

$*$ All this functionality is provided via NcAstrolab

Exercises

- Consider the Westerbork radio telescope at $52^\circ\,54'\,54.33''$N $6^\circ\,36'\,12.74''$E.
  At 06-sep-2011 21:10:34.7 UTC one wants to observe the Andromeda galaxy.
  Andromeda galaxy (M31) : $\alpha = 0\text{h}\,42.7\text{m} \quad \delta = 41^\circ\,16'$ (J2000)

∗ What are the horizontal coordinates to aim the telescope at ?

- Consider the IceCube experiment at the South Pole.
  The experiment uses the following righthanded local coordinate system :
  Z-axis points to Zenith, Y-axis points North, X-axis points East.
  At 15-aug-2009 06:23:16.2 UTC we observed a very energetic muon track.
  Track direction $\theta = 12^\circ \quad \phi = 138^\circ$

∗ Provide the Equatorial and Galactic coordinates of the source.

∗ Show the location of the source on an Equatorial and Galactic skymap.
  Hint : Use NcAstrolab

Exercises

- **Cosmic rays impinge on the Earth's atmosphere from all directions. The resulting angular distribution is isotropic.**

∗ **Generate arrival directions for 1000 cosmic rays and use NcAstrolab to show that the observed angular distribution is indeed isotropic.**