Observational Astronomy in the Optical/IR

Basics II: Effects on Celestial Positions & Time

"We'd like to study the effects of gravity, loud music, and beer on astrophysicists."

David Buckley
SALT Project Scientist
SAAO

Effects on Apparent Celestial Positions

- **Long time-scale variation due to ‘wobbling’ of the Earth’s rotation axis: precession & nutation**
  - Gradual changes in the coordinate system over time (repeating every ~26,000 years)
  - Due to gravitational effects of mostly Moon & Sun (also planets) on the non-spherical Earth

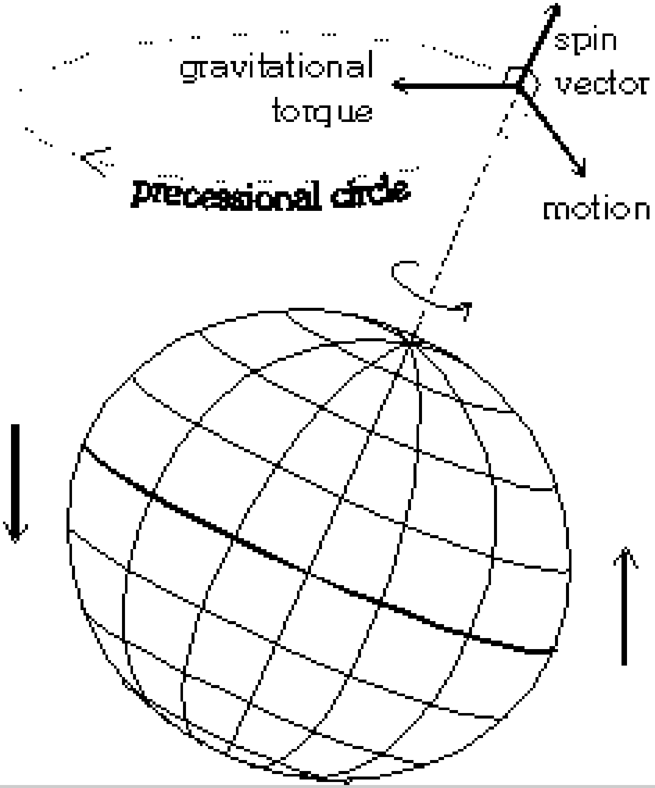
- **Periodic variations: aberration and parallax**
  - Changes apparent position cyclically
  - Daily (“diurnal”); yearly (“annual”)

- **Earth’s atmosphere: refraction effects**
  - Changes apparent position as a function of Zenith Distance

- **Secular variations: due to the real space motion of objects (particularly Solar System object and nearby stars)**

Effects on Apparent Celestial Positions

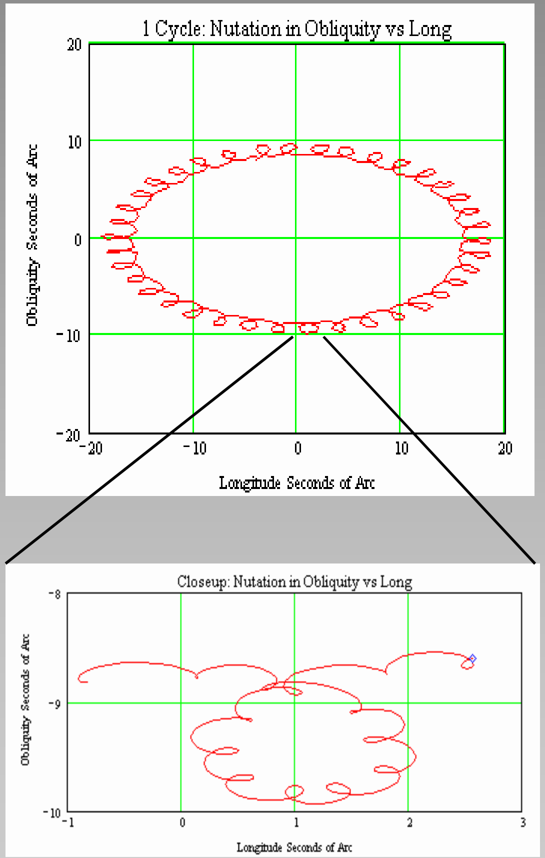
- **Precession**
  - Discovered by Hipparchus in 125BC
  - Compared star positions measured ~150 years apart
  - Deduced a ~50 arcsec motion in longitude (λ) of the equinox nodes
  - Period of precession is 25,740 years about the ecliptic poles
  - Due to gravitational torque of Moon, Sun & planets acting on the spinning, non-spherical Earth

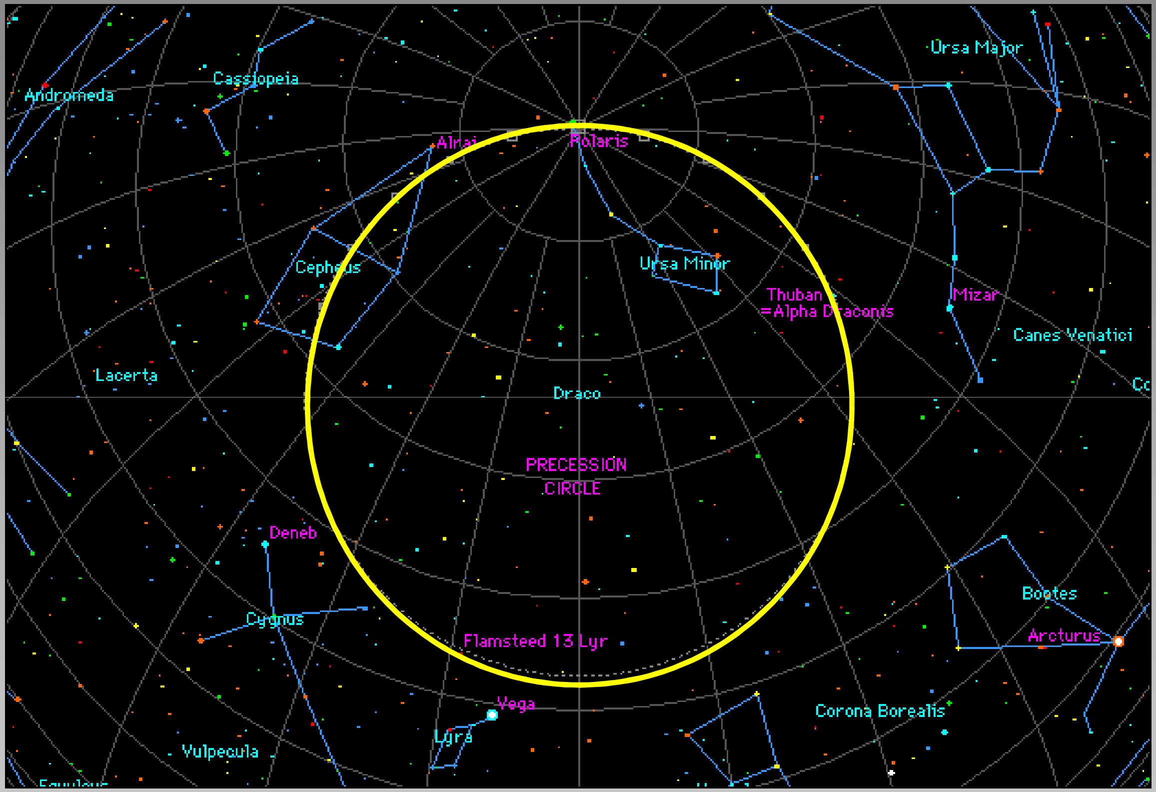


- **Nutation**
  - Due to Moon’s non-circular orbit and precession of nodes of its orbit with a period of 18.6 years
  - Produces an additional “nodding” motion on the Earth’s axis
  - Quite complex, with many non-harmonic components (106!) for Moon/Sun/planet interactions

Effects on Apparent Celestial Positions

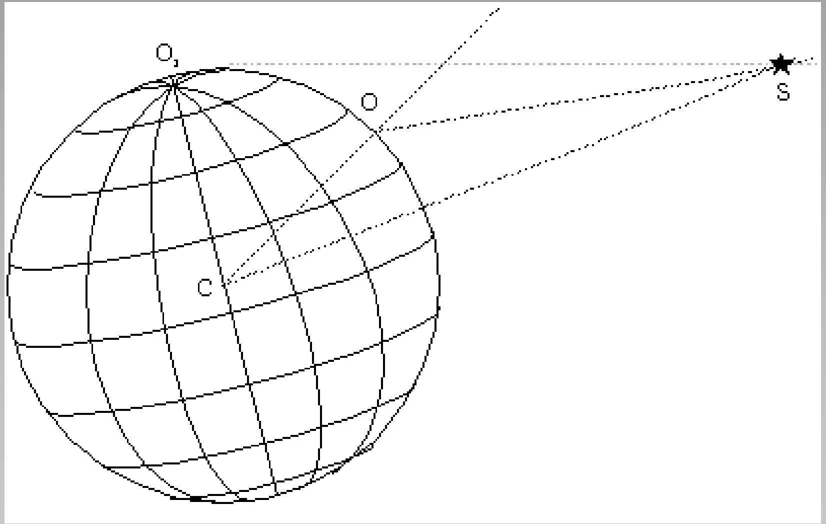
- **Precession & Nutation**

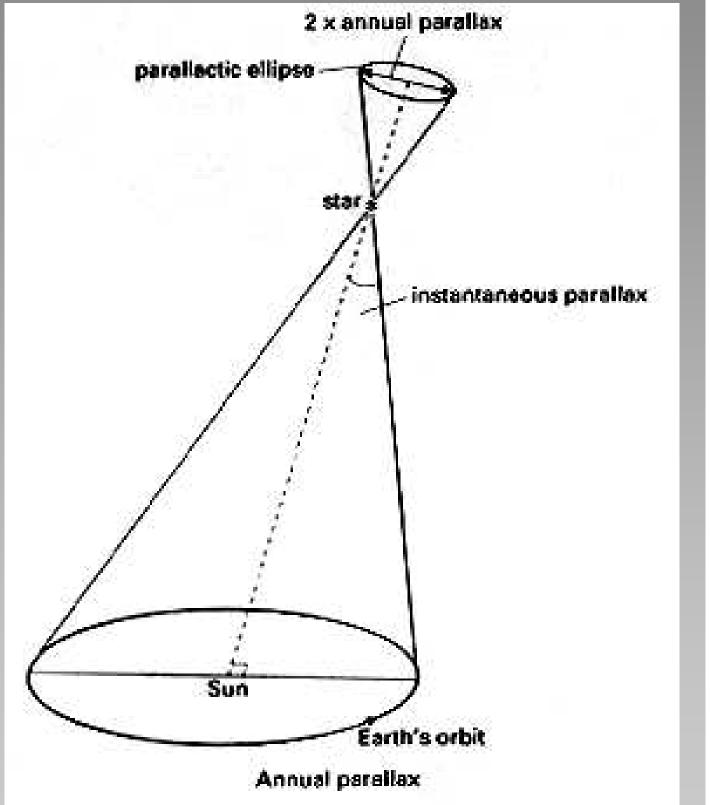




Parallax

- **Close enough objects can vary in *apparent* position on the celestial sphere because of:**
  - Varying viewing position on the Earth (geocentric parallax)
  - Varying viewing position due to Earth’s rotation (diurnal parallax)





  - Varying viewing position due to Earth’s orbital motion (annual parallax)

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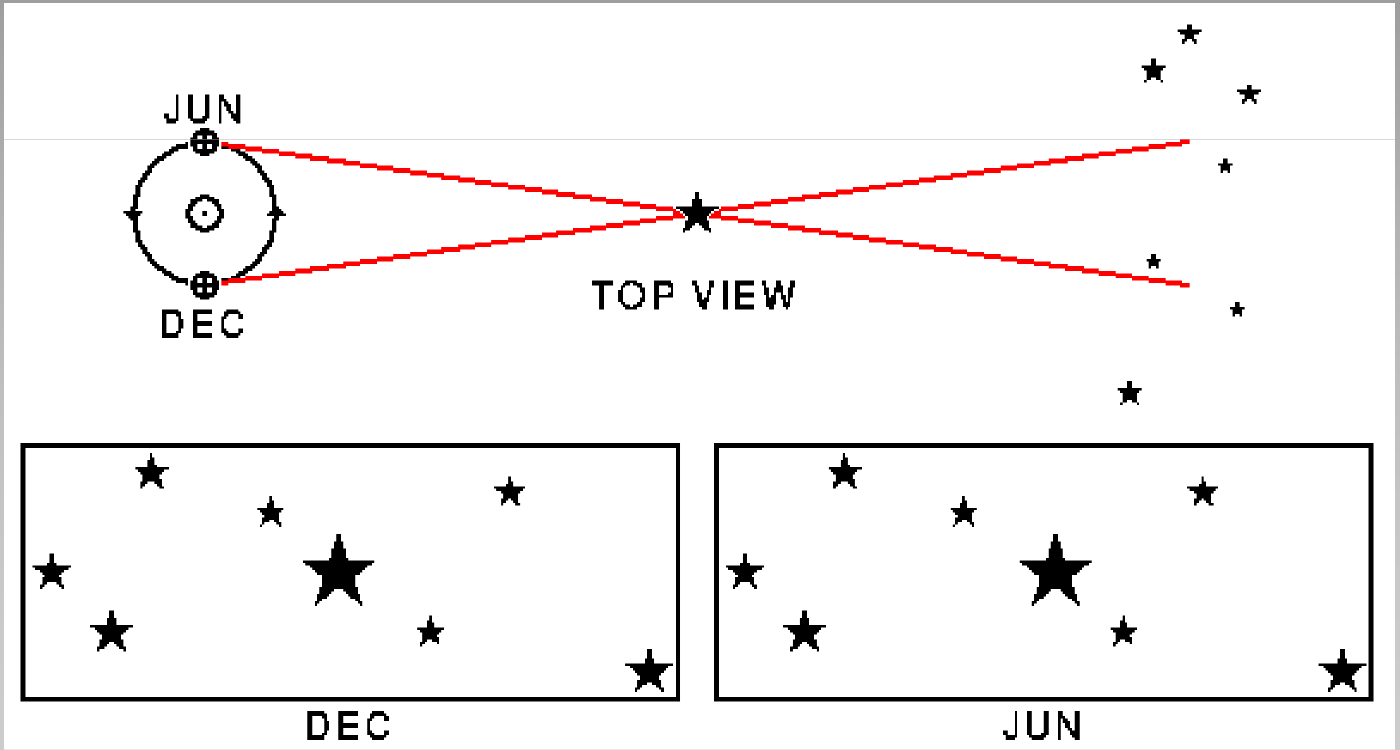
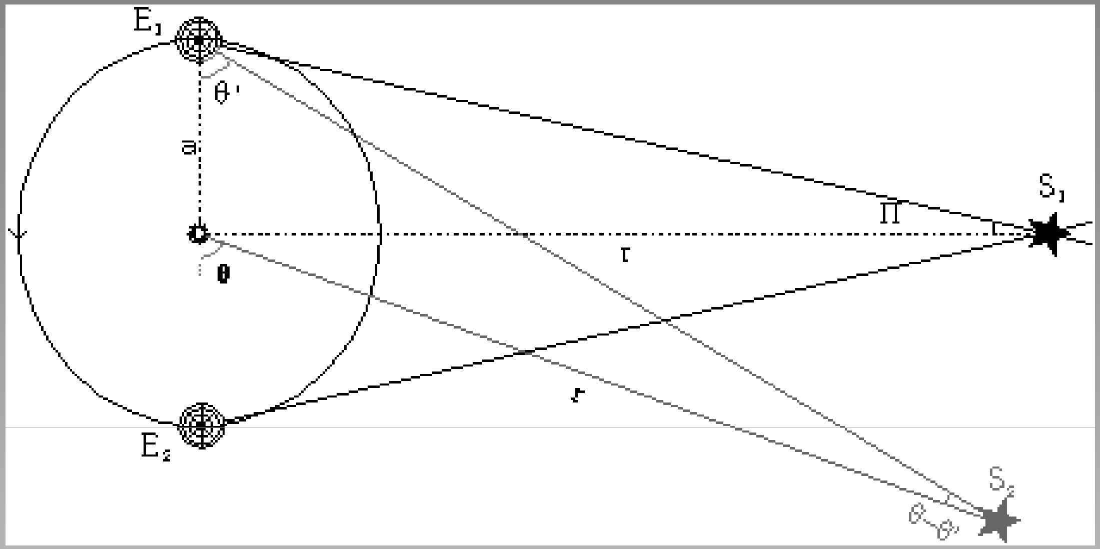
Annual Parallax

- Standard method to determine the distance to the nearest stars
- Close enough stars can vary in their *apparent* position on the celestial sphere, usually detected by reference to much more distant stars (major research program at the Cape until 1960's)



Annual Parallax



Formulae for calculating parallax:

$\tan \pi = a / r$ since $r \gg a$ $\Rightarrow$ π (in radians) $= a / r$

Definitions:

- *a = mean Earth-Sun distance (149,597,871 km) = 1 Astronomical Unit (AU)*
- *π is measured in arcseconds (where there are 206,265 arcseconds in a radian)*
- *R is measured in parsecs (pc), where:* $\pi\,(\text{arcsec}) = \dfrac{1}{r(\text{pc})}$

[So 1 pc = 206265 AU ~ 3.09×10^{13} km ~ 3.26 Light Years]

Other Position-Changing Effects

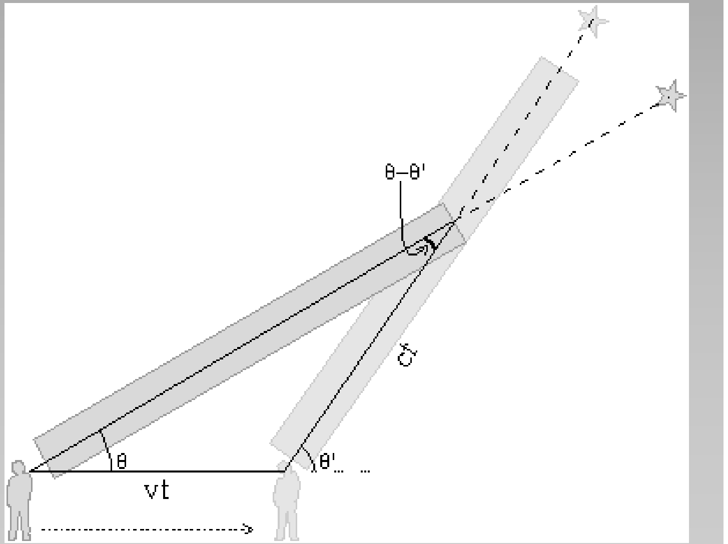
- **Proper Motion**
  - *Due to the real space motion of stars within the Galaxy*
  - *Relative motion between star and the Sun (which is moving at ~200 km /s in its orbit around the Galaxy)*
  - *Only really noticeable with ground based telescopes on the nearest or fastest moving stars (e.g. white dwarfs)*
  - *Satellite observations have/will improve information on proper motions (e.g. Hipparcos & Gaia)*

- **Aberration of Starlight**
  - *Due to finite speed of light and Earth's velocity*
  - *Need to add motion vector of Earth to light vector*
  - *Results in small position shift* $\Delta\theta \;=\; k \sin\theta$

    k = 20.47 arcsec for Earth's orbital velocity (annual)

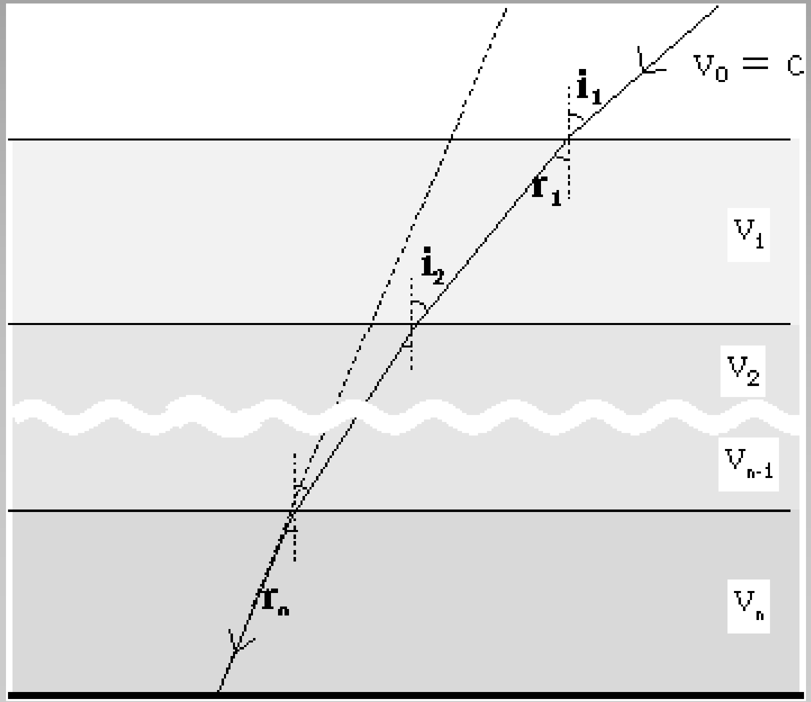
    k = 0.32 arcsec for Earth's rotational velocity
  - *Annual aberration causes stars to move in ellipses*

    a = k   b = k sin β; so on ecliptic, stars move in lines and at ecliptic poles they move in circles



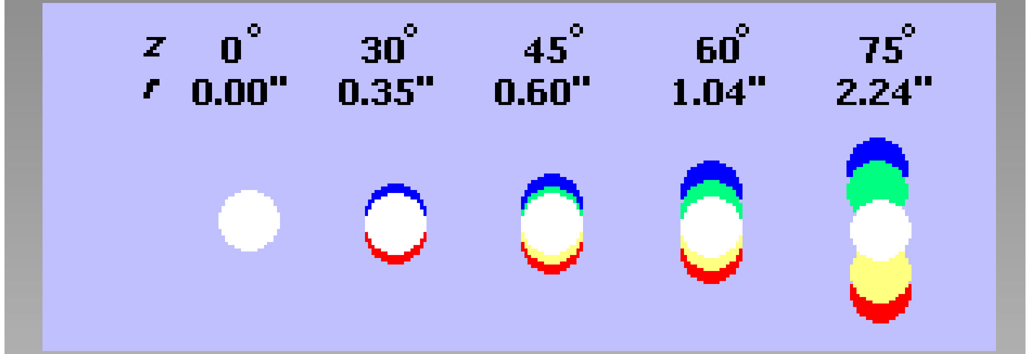
Other Position-Changing Effects

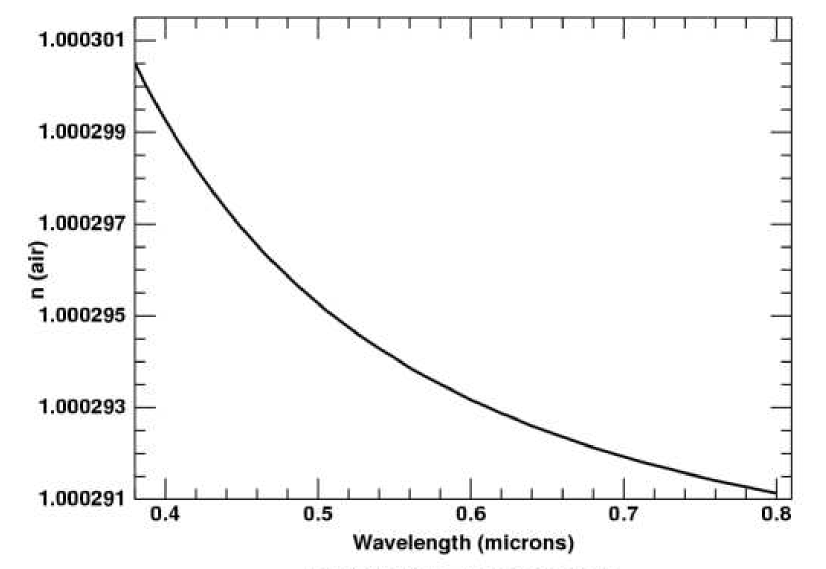
- **Atmospheric Refraction**
  - *Earth's atmosphere acts like a lens due to the layered behavior of the index of refraction of the atmosphere*
  - *Refraction effects more apparent for higher angle of incidence ⇒ larger Zenith Distances of objects*



Atmospheric Refraction

- **Atmospheric Refraction**
  - *Because index of refraction is wavelength dependent, positions change with wavelength and zenith distance*





Refractive index of air

  - *Images are dispersed into small spectra*
  - *Calculate effect by applying Snell's Law (and assume plane parallel atmosphere)*
  - *Result is that angular offset can be expressed as:*

$$R = z_{true} - z_{observed} = k \tan z_{observed}$$ (for z <60º)

where: $$k \text{ (in arcsecs)} = 206265 \times [\mu - 1] = \frac{16.27 \times P \text{ (millibars)}}{T\ (^{\circ}K)}$$

and: *μ is the index of refraction of air at ground level*

For standard temperature (273ºK) & pressure (1000 millibars), k = 59.6 arcsec

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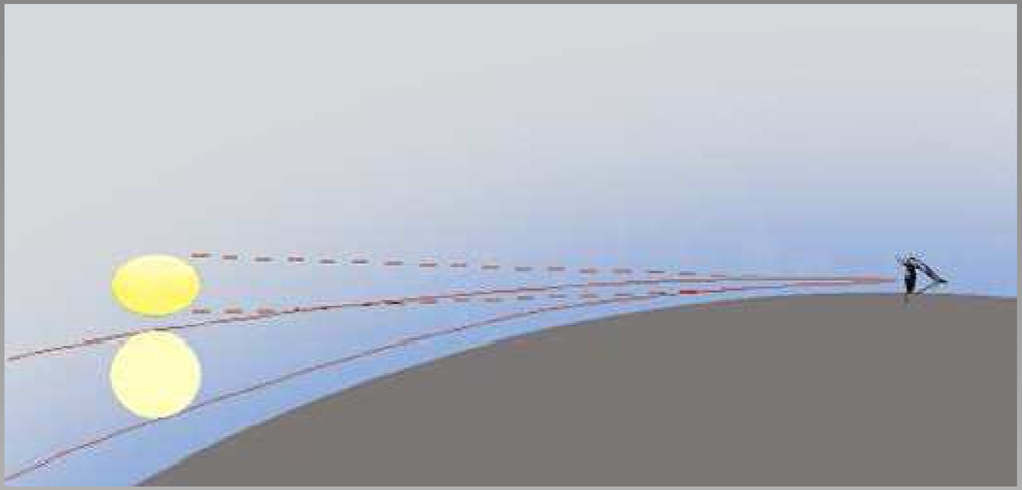
Atmospheric Refraction Effect on Setting/Rising Sun



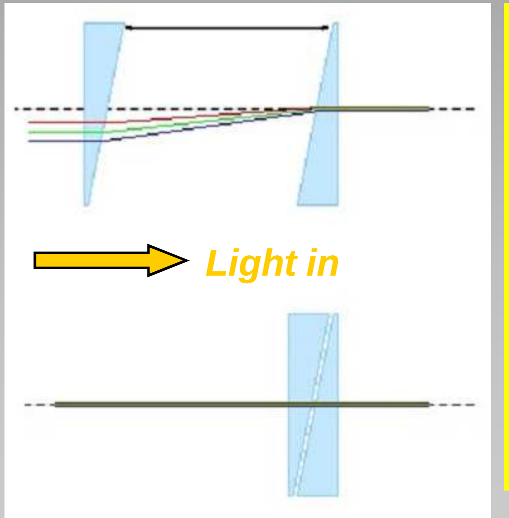
Atmospheric Refraction

- **An example: the setting Sun**

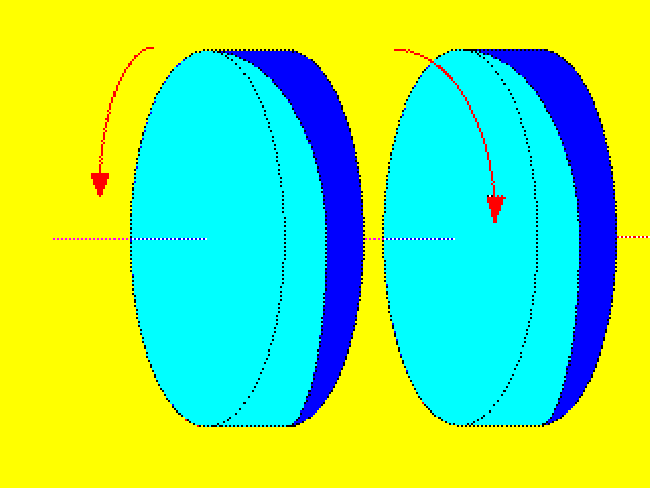
- *The "Green Flash": look for it at sunset on a clear low horizon (e.g. Seapoint)*

Atmospheric Dispersion

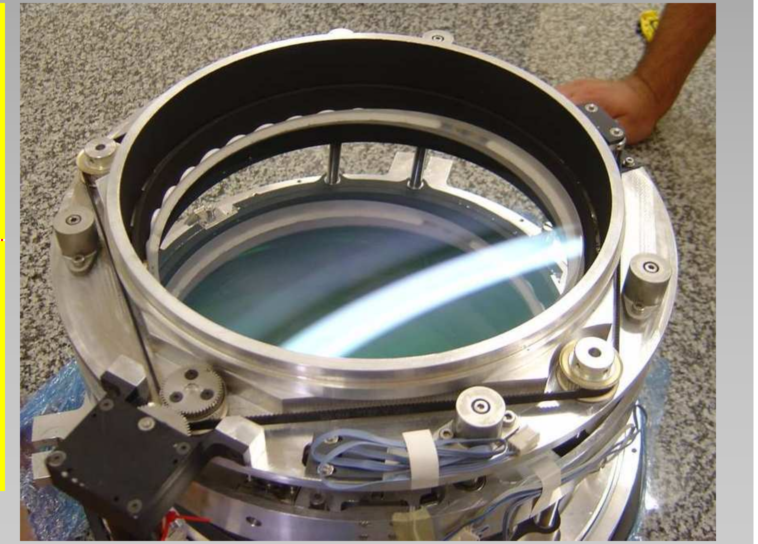
- **Atmospheric Dispersion Compensation**
  - ***Because atmospheric dispersion is an optical effect, it can be corrected at the telescope with optics.***
  - ***We can remove the refractive effect of the atmosphere and thus restore stretched out images to be the same as if they were observed at the zenith***
    - » *This does NOT mean we can remove the turbulent effects of the atmosphere which cause phase changes in wavefronts, resulting in blurry images much larger than the diffraction limit. That is achieved with Adaptive Optics (a topic in a future lecture).*



Translating prisms



Counter-rotating prisms



SALT Atmospheric Dispersion Compensator (ADC)

Basics II: Effects on Celestial Positions & Time

Time

Time is complicated!

- **The *Astronomical Almanac*** (used to be the standard observer’s handbook before computers. Some ‘old hands’ still use it and its full of interesting stuff!) **lists no less than a dozen different time systems!**
- **For astronomical measurements its crucial to know what time system is being used** (particularly for time varying or time critical phenomena, like eclipses, periodic variations in stars or coordinating observations from different observatory on ground and in space).

Two major way of measuring time:

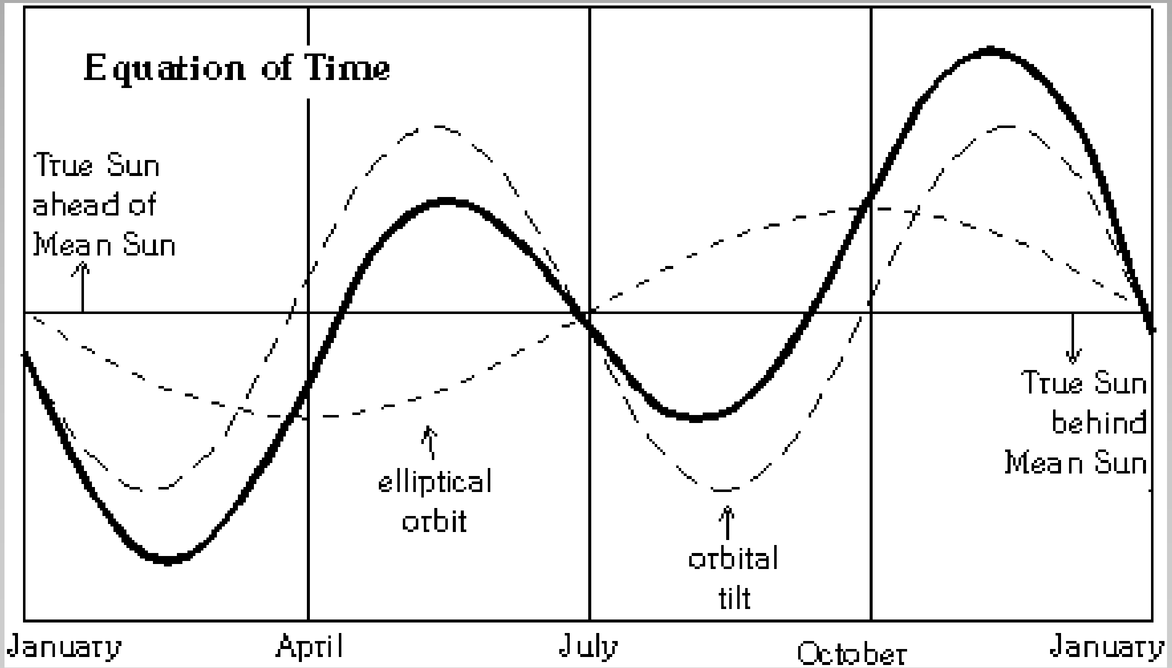
- ***With respect to the rotation of the Earth***
  - ***But rotation rate is not uniform and results in secular (long-term) changes of the order of ~ 1 sec per year.***
  - ***Up until atomic clocks, Ephemeris Time (used until 1984) was the standard, which used the best theory of Earth’s rotation.***
- ***Using the frequency of atomic oscillations***
  - ***Since the 1950’s, atomic time, which is accurate to microseconds (10^{-6}) per year, has taken over***

Earth Rotation Times

- Local Apparent Time
  - Based on when the Sun crosses the meridian each day
  - So as to start a new day at midnight rather midday, this is defined as:
    - » Solar Hour Angle + 12 hours
  - This implies that local Noon is when the Sun is at its highest in the sky and that different longitudes would have different time
    - » Very confusing for people travelling in longitude
  - But even local Apparent Time is not strictly constant due to:
    - » Eccentricity of the Earth’s orbit, which means the Sun’s distance changes over a year and therefore its apparent ***angular motion*** on the sky changes
    - » The Earth (and therefore the Sun’s projection on the celestial sphere) moves ***faster*** at perihelion (closest approach) in July and ***slowest*** at aphelion (furthest separation) in January.
    - » Obliquity of the ecliptic: the Sun’s varying velocity in ***ecliptic longitude***

Effects of Earth's Rotation

- **The Equation of Time**
  - **Because of the Earth's orbital eccentricity and its axis tilt (obliquity), time measured by the Sun's position varies throughout the year**
  - **Correct for this using the *equation of time***
  - **This applies a correction to the time derived from the Sun's position (e.g. from a Sun dial) to account for these affects.**
  - **The corrected time is referred to as the *Mean Time* which is defined by a fictitious Sun (the *mean* Sun) having a constant velocity around the celestial equator.**



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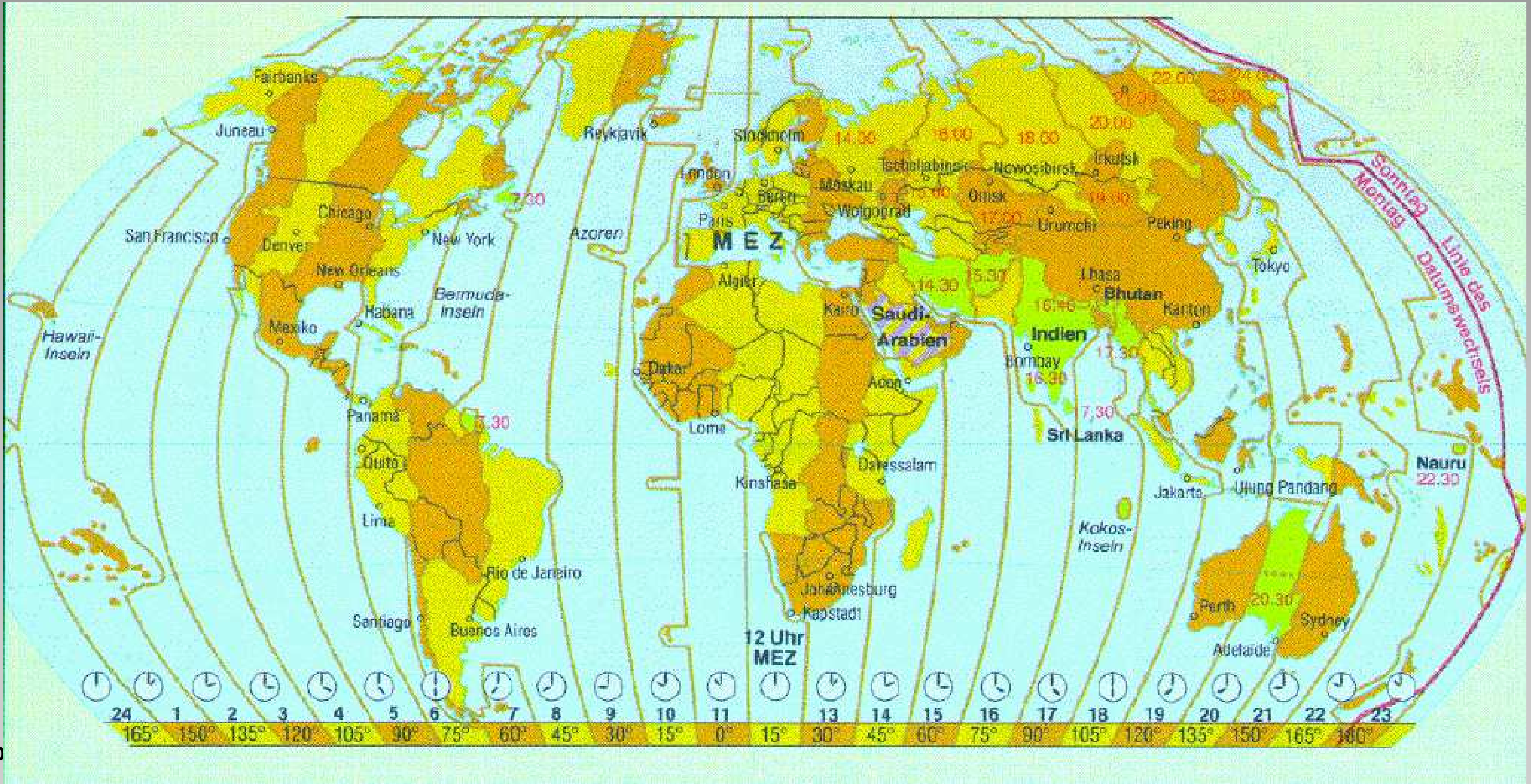
Greenwich Mean Time (GMT)

- **Defined by the location (Hour Angle) of the *mean Sun* at Greenwich**
- **So 12:00:00 GMT is when the mean Sun crosses the meridian at Greenwich**
- **In order to avoid the complexity of every place on Earth operating on their *Local Mean Time,* a system of *time zones* was set up 100 years ago**



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Universal Time (UT or UT1)

- **Different versions of “universal times”, but most are defunct now or not widely used anymore (e.g. UT0, UT2, UTS)**
- **The one in wide usage is UT1, or simply called UT**
  - **A measure of the true rotation period of the Earth with respect to a fixed frame of reference. As this not uniform, UT1 has an uncertainty of ± 3 milliseconds per day, implying drifts of ~1 sec per year with respect to atomic clock time (TAI).**
  - **Essentially the same as GMT.**
  - **It is the same everywhere on Earth.**

Greenwich Mean Sidereal Time (GMST)

- **Measures the Hour Angle of the mean Vernal Equinox (♈) at Greenwich**
- **Accounts for precession but not short-term nutation (the correction for nutation is defined as Greenwich Apparent Sidereal Time or GAST)**
- **IAU convention links GMST and UT1 through a formulae (see notes) based on Julian Date (to be defined later)**

Local Mean Sidereal Time (LMST)

- ***LMST = GMST + observers east longitude (in time)***
- ***Usually the same as just LST (= Hour Angle – R.A.)***

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Atomic Times

- *Based on atomic transitions and reaching accuracies of 10^{-15} to 10^{-17} sec*
  - Keeping time to 1 sec in 3 billion years!
  - Need to take account of General Relativity effects (gravitational redshift) by correcting for their mean altitude above sea level
- *International Atomic Time (Temps Atomique International, or TAI)*
  - SI unit of time based on 9.19 GHz transition between to hyperfine levels of the ground state of Cesium 133 (microwaves)
  - TAI is Earth-based system (dependent on the gravitational potential) and is a weighted mean time from ~200 atomic clocks around the globe
- *Co-ordinated Universal Time (UTC)*
  - Time broadcast by various international standards organizations e.g. the National Institute of Standards and Technology (NIST; formerly National Bureau of Standards) in the U.S.A.
  - UTC has the same rate as TAI (i.e. their seconds are identical)
  - Due to previously mentioned slowing spin of the Earth, need to add leap seconds to UTC from time to time to ensure mean solar noon (at Greenwich) always occurs at the same UTC (12:00:00) and so UTC is kept within ~ ±0.7 sec of UT1

Basics II: Effects on Celestial Positions & Time

- *Ephemeris Time (ET) & Terrestrial Dynamic Time (TT)*
  - **ET used before widespread use of atomic clocks and was the closest to a uniform time**
  - **ET replaced in 1984 by TT, which is based on TAI**

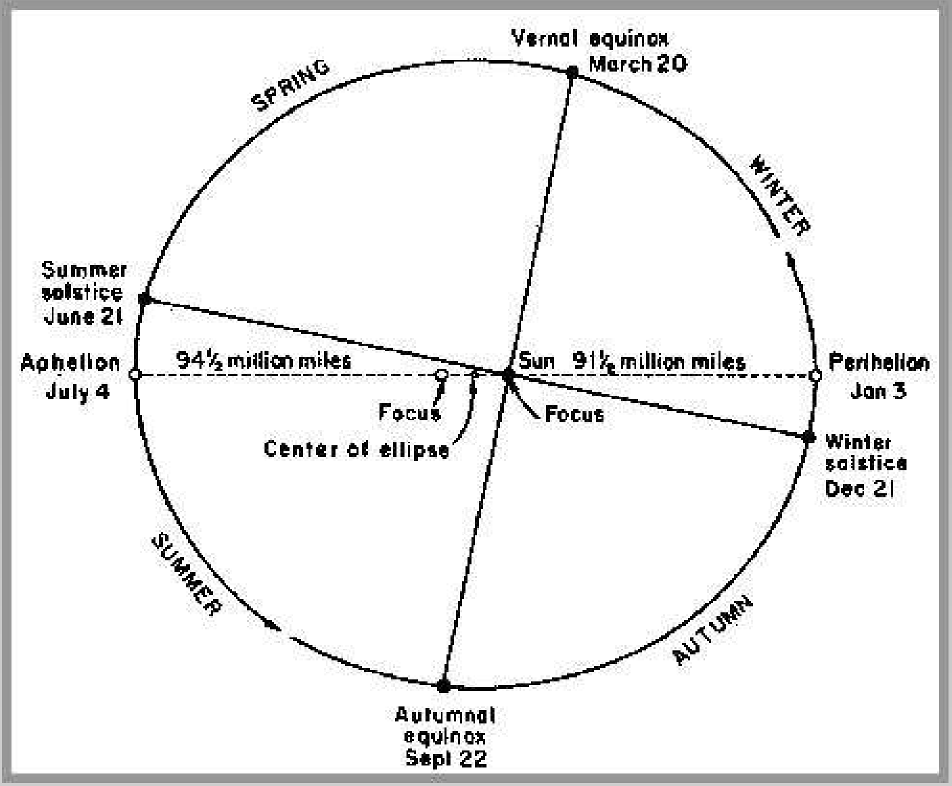
- *Barycentric Dynamic Time (BDT)*
  - **Similar to TT, but corrections are made to move the origin from Earth's gravitational field to the barycentre of the Solar System (within the Sun)**
  - **The difference only amounts to 1.6 milliseconds an is only relevant for the timing extremely fast phenomena (e.g. millisecond pulsars)**

Years

- ***Tropical Year***
  - *The time between two successive passages of the mean Sun through the Vernal Equinox = 365.2421988 days (UTC) and is decreasing by 0.53 sec per century*
  - *"Natural" yearly timescale since it defines the seasons*
- ***Sidereal Year***
  - *The time between two successive passages of the mean Sun with respect to the distant stars = 365.256366 days (UTC)*
  - *Longer than a Tropical Year due to the retrograde motion of the Vernal Equinox (♈) due to precession*

Years

- *Anomalistic Year*
  - *Interval between two successive passages of the Earth through perihelion = 365.259636 days. Longer than Sidereal Year due to precession of the line of apsides (semi-major axis of Earth's orbit).*



Years & Calendars

- *Civil Year*
  - ***For "civil" purpose, a year should:***
    - *Contain integer numbers of days*
    - *Stay in phase with the seasons*
  - ***Achieved by having repeat cycles of***
    - *3 years of 365 days*
    - *1 year of 366 days (leap year)*
    - *Average length of year over this 4 year cycle is 365.25 days*
    - *Very close to the length of a Tropical Year (365.2422 days)*
  - ***This was the basis of the Julian calendar***
  - ***Difference amounts to ~8 days over 1,000 years***
    - *Calendar reformed in 1582 by Pope Gregory XIII (Gregorian calendar)*
    - *Modification of Julian calendar (3 days every 400 years are omitted)*
    - *Now the error is reduced to ~1 day every 4,000 years*
    - *The revised rule for a leap year in the Gregorian calendar is*
      - *Year divisible by 4; except years which are multiples of 100; unless they are divisible by 400*
      - *2004, 2008, 2012… are leap year; 1700, 1800, 1900 are not; 1600, 2000, 2400 are*

Julian Dates

Julian Day Number, or Julian Date, was adopted to avoid complications calculating elapsed time with calendars

- **Devised by Josephus Scaliger (1540 – 1609) and named, not for Julius Caesar (as Julian Calendar was), but probably his father!**
- **Day 0 in Julian Date is 1 January 4713 BC at 12:00:00 GMT (what a day!)**
    - **Why? What's so significant about this date, some 6,720 years ago?**
    - **Chosen because 3 important (*back then!*) cycles, extrapolated back in time, were all in phase and beginning together on that date:**
        - » *The 19 year Lunar Metonic cycle*
        - » *The 15 year Indiction Cycle (a Roman taxation cycle! Tell SARS)*
        - » *The 28 year Solar Cycle of the Julian calendar (nothing to do with Sunspots!)*
    - **Julian Date today (20 Feb 2011 at 15:00 (13:00 UTC) is 2455978.0476**
- **Since JD starts at Noon, this means over a given night in Europe/Africa that the JD has the same integer value**
- **Because JD is a long number (7 digits before the decimal!), sometimes the abbreviated *Modified Julian Date* (MJD) is used**
    - **MJD = JD - 2450000.5000**
    - **So MJD changes day at midnight UTC instead of 12:00 UTC**

Julian Dates

- ***Heliocentric Julian Date***

This is a further modification to Julian Date to take account of the following:

- **As the Earth moves around its orbit, it changes its distance with respect to objects being observed**
- **Due to the finite speed of light, the distance changes can lead to timing changes**
  - **When observing time varying phenomena (e.g. eclipses) we have to account for the different light travel times**
  - **Correction varies systematically over the orbit**
  - **Can amount to a ~17 minutes delay comparing timing from one side of the orbit (when closest to the object) to the other side (when furthest away)**
- **The times are therefore corrected to a time as if the observation was taking place at the centre of the Sun, hence heliocentric**
- **The correction is:**

$$HJD = JD + K\,R\,(\cos L \cos\alpha \cos\delta + \sin L\,(\sin\varepsilon \sin\delta + \cos\varepsilon \cos\delta \sin\alpha))$$

Where:

K = **Mean Sun-Earth travel time (0.000578 days),**

R = **Ratio of true Earth-Sun distance to mean Earth-Sun distance**

L = **longitude of Sun,** ε = **obliquity of the equator (23º 26’ 21.448” for 2000.00)**

α, δ = **Right Ascension & Declination coordinates of the object**

Julian Dates

Barycentric Julian Date (BJD)

- **For the most accurate timing (e.g. milliseconds or microseconds) of phenomena**
- **Corrects for time from the perspective of the barycentre (centre of gravity) of the entire Solar System.**
- **Takes out the slight wobble of the Sun produced by the gravitational forces of the planets**
- **Dominated by the effect of Jupiter**
- **Amplitude of the difference between HJD (Sun-centred) and BJD (Solar System Centred) is ~4 sec over the 11 year orbital period of Jupiter**