Observational Astronomy

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A 32,500-year-old star chart?

Astronomical alignments
e.g. Stonehenge c.5000 yr old

A Brief History of Observational Astronomy

Armillary spheres and astrolabes

- Independently invented in China and Greece c. 200bce
- Chaucer wrote a treatise on the astrolabe in 1391

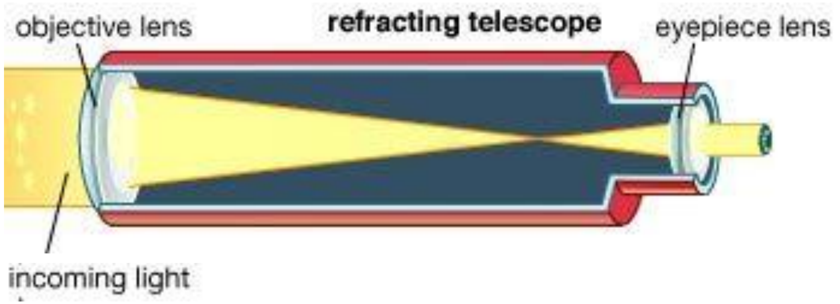
The Antikythera Mechanism – a calendar and orrery from c.100bce

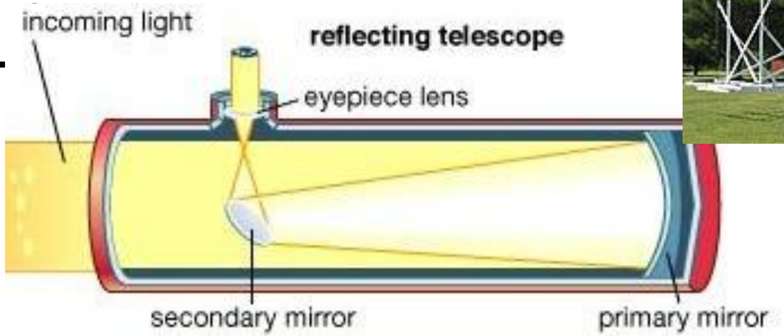
- It took 1500 years to make similarly complex astronomical clocks – e.g., Samuel Watson of Coventry (1690)

- Can show planetary orbits, dates, times, lunar and solar cycles, eclipses.

- *In the collection of Windsor castle (image reproduced from Royal Collection Trust / © Her Majesty Queen Elizabeth II 2021)*

The First Telescopes





1608: Hans Lippershev/ Jacob Metius 16:08: Gallileo Gallilei 16:11: Johannes Kepler	All Refracting Telescopes which may have been around decades (or even longer) before
1668: Issac Newton	Reflecting Telescope was proposed earlier
1936: Karl Jansky	Radio Telescopes
1963: Riccardo Giacconi	X-Ray Telescopes
1968: Nancy Grace Roman	Space Telescopes – OAO-2

Key Questions to Consider:

Where is your target?

- coordinate systems
- precession of the equinoxes
- proper motion

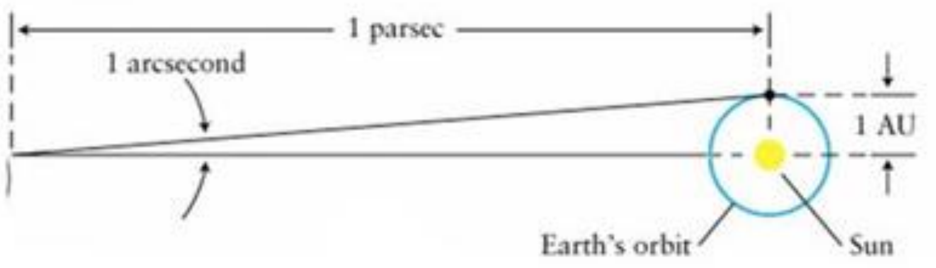
When can you observe it?

- equatorial vs alt/az
- hour angles
- how do we measure time?

What effect will the atmosphere have?

- atmospheric refraction
- atmospheric extinction
- seeing and sky brightness
- adaptive optics

Angles



Observational Astronomy is all about ***angles***.

1 ***AU*** at 1 ***pc*** subtends 1 ***arcsecond*** = 1”

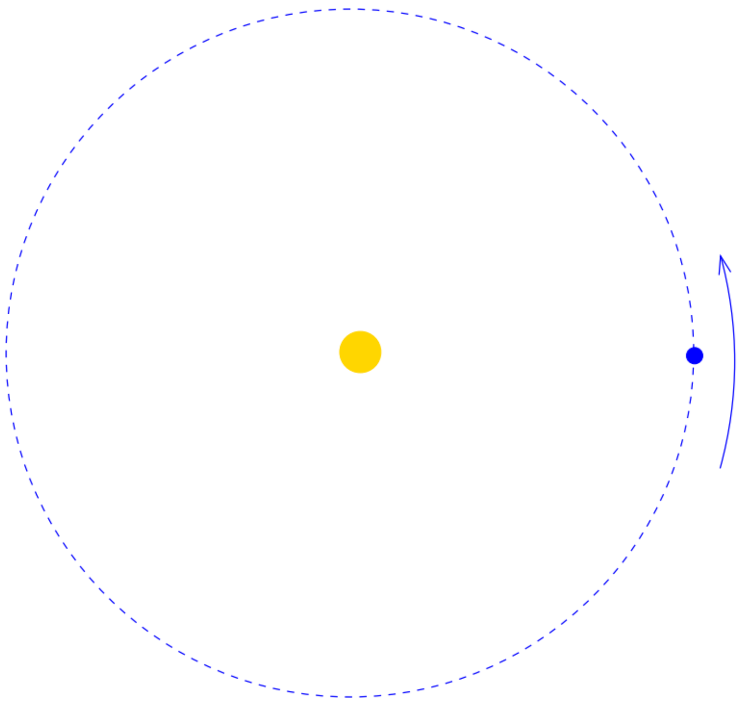
- This is an angular measurement equal to 1/3600 of a ***degree***.
- There are 206,264.5" in a ***radian***.
- An ***arcminute*** (‘) is equal to 1/60 of a degree or 60"
- Therefore, $1'' = 1/60' = 1/3600^\circ = 1/206264 = 4.848 \times 10^{-6}$ radians

Angles often written in the sexagesimal form inherited from the Babylonians.

For example: $10^\circ\ 24'\ 56.3'' = 10+24/60+56.3/3600 = 10.415639^\circ$

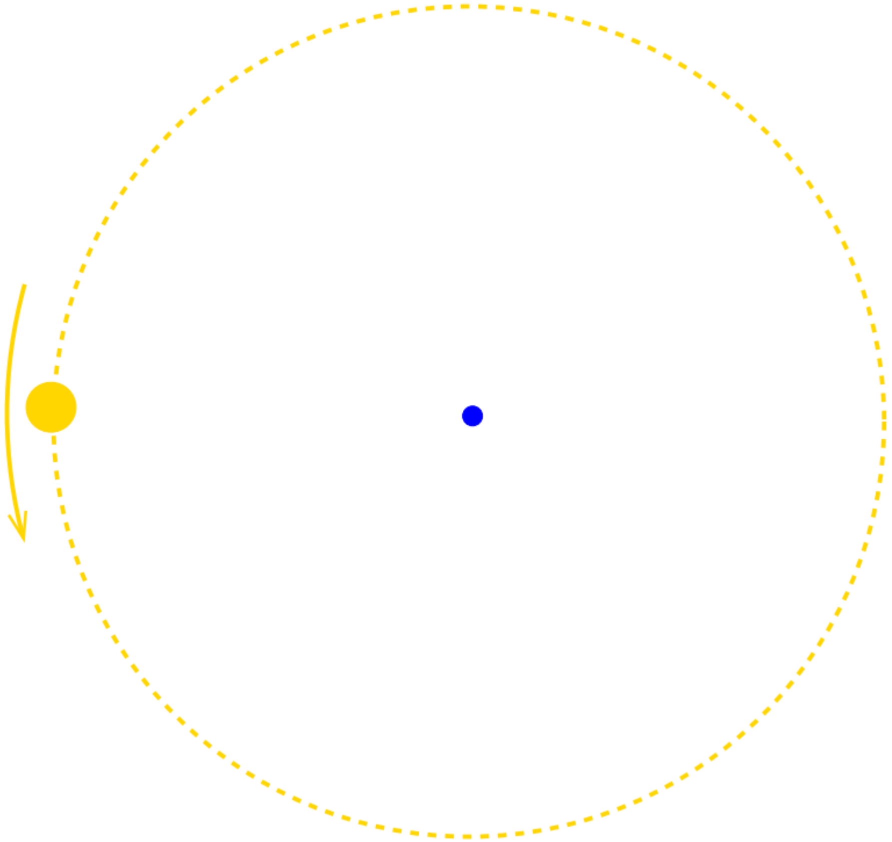
Sun & Earth

We all know the Earth goes round the Sun anti-clockwise when viewed from above the North Pole.



Earth & Sun

- For observing, it's sometimes convenient to adopt a Ptolemaic Earth-centred view where the Earth is the centre of the geocentric model (only aberration and parallax disturb this picture).
- The Sun also goes anticlockwise.



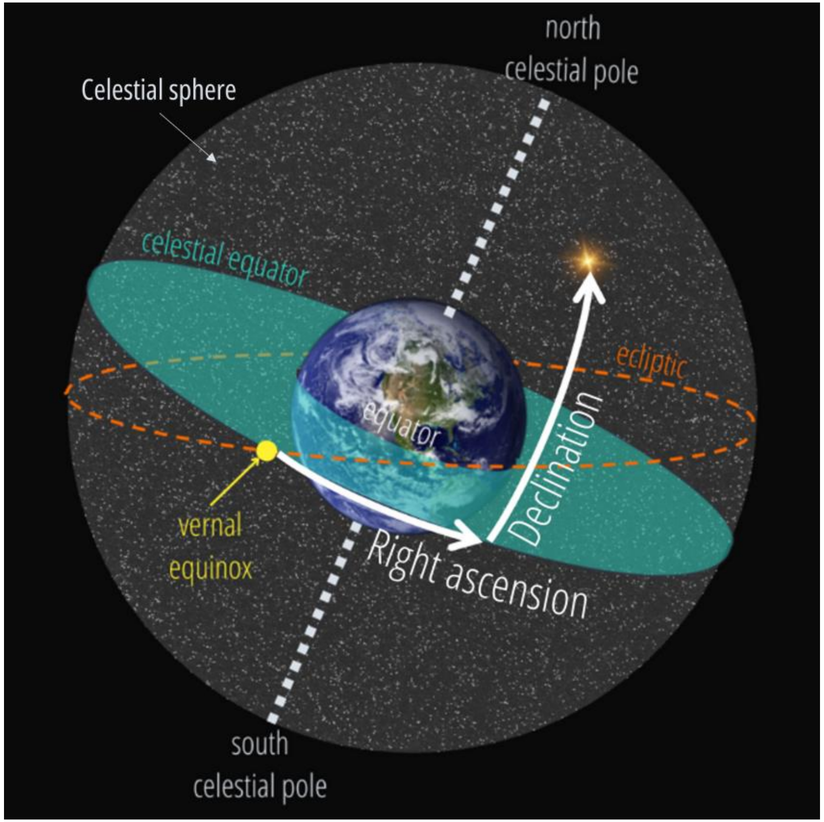
Declination

- Earth's rotation axis defines a natural polar axis.
- ***Declination*** is equivalent to ***latitude*** on Earth
- It runs from -90° to +90°, south to north pole.

Star trails from Tenerife, latitude +28°

Right Ascension

- The equivalent of ***longitude*** is ***Right Ascension (RA)***.
- It is measured from the point where the Sun crosses the equator in spring (vernal equinox, also known as the "first point of Aries", but nowadays in Pisces due to precession/constellation definition).
- RA goes from 0 to 24 hours.
- Often measured in sexagesimal HH:MM:SS.SS
- Sun at RA ~ 0 h, 6 h, 12 h, 18 h on Mar 21, Jun 21, Sep 21 and Dec 21 , respectively.



Right Ascension in degrees

- RA goes from 0 to 24 hours in increments of 15° per hour.

So,

RA = 15:22:33.02 corresponds to:

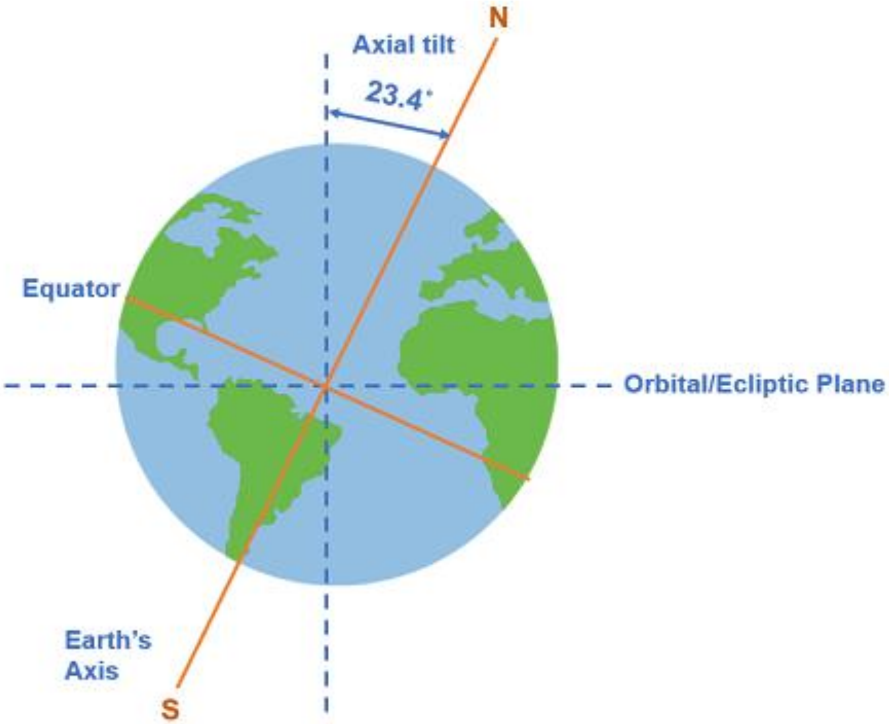
$15*(15+22/60+33.02/3600) = \underline{230.63758°}$

It is common to see in the literature and for both styles to be used!

Ecliptic

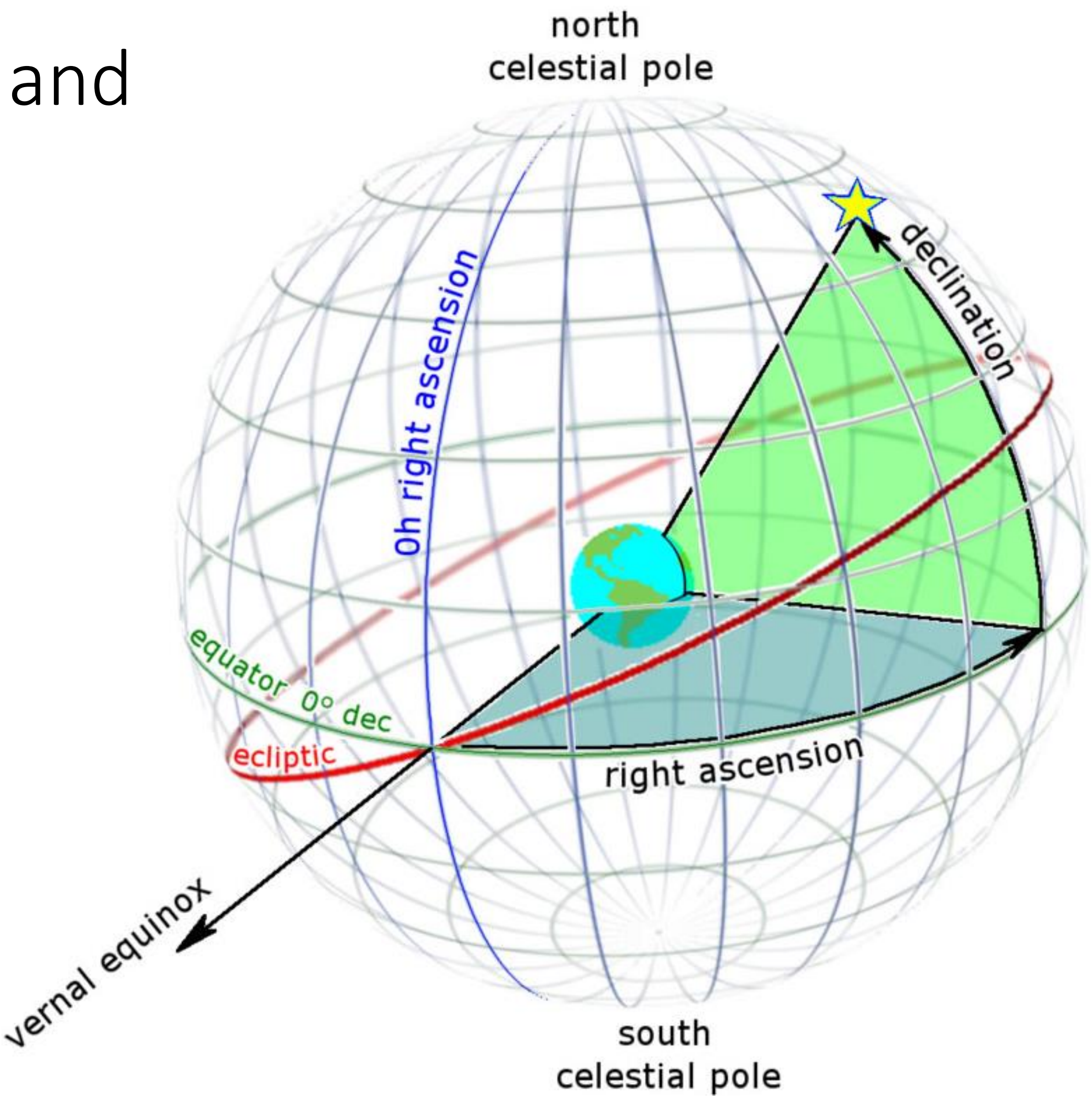
- Over the year the Sun traces out a great circle on the sky – the ***ecliptic***.
- The ecliptic is tilted at 23.4° to the equator due to tilt of the Earth's axis relative to its orbital axis.

Therefore, adding in declination, the Sun is at:
(RA,Dec) = (α,δ) = (0^h,0°), (6^h,23°), (12^h,0°),(18^h,-23°)
on the
21st of Mar, Jun, Sep and Dec.



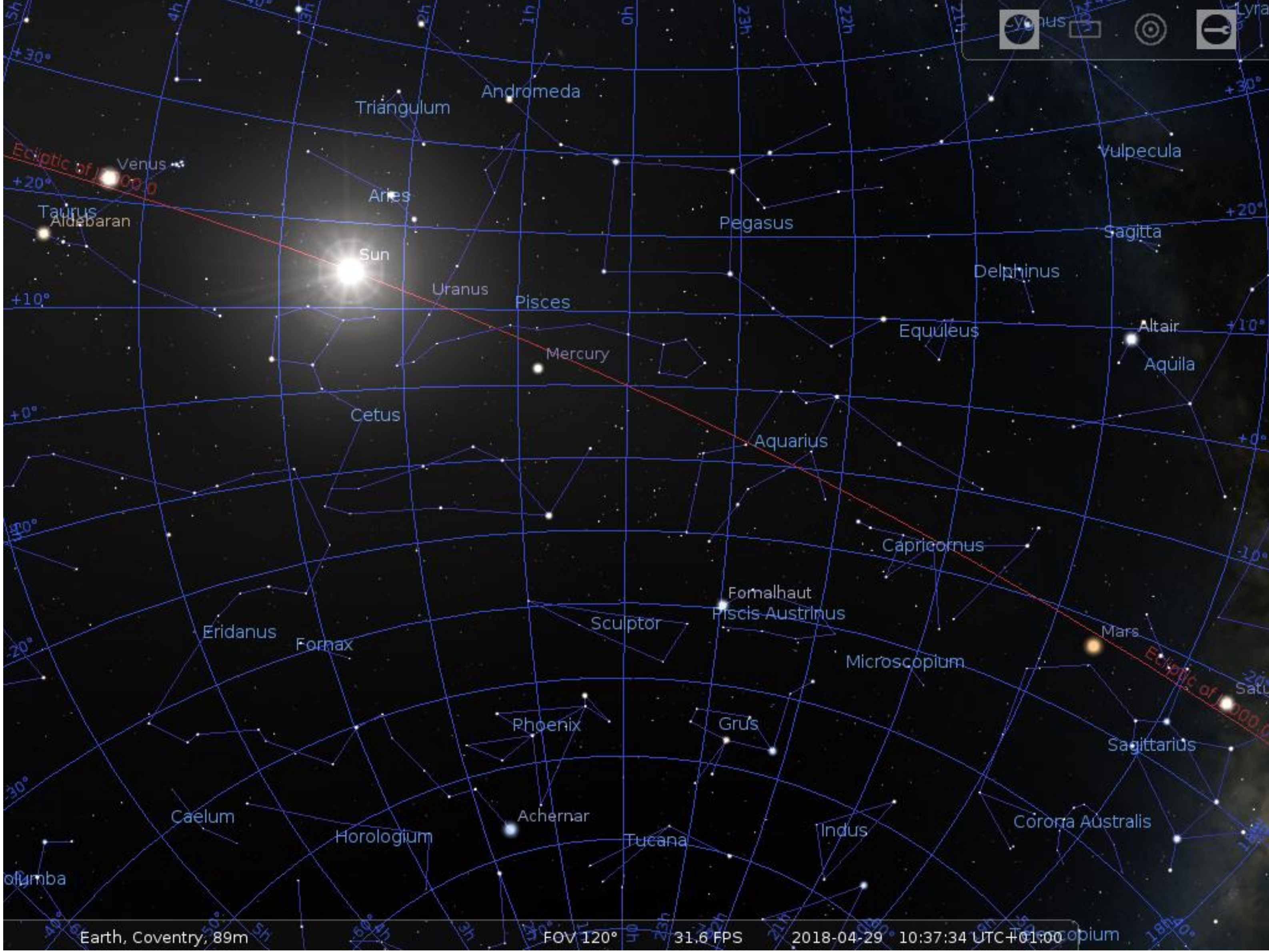
Right Ascension and Declination

Image: https://skyandtelescope.org/astronomy-resources/right-ascension-declination-celestial-coordinates/



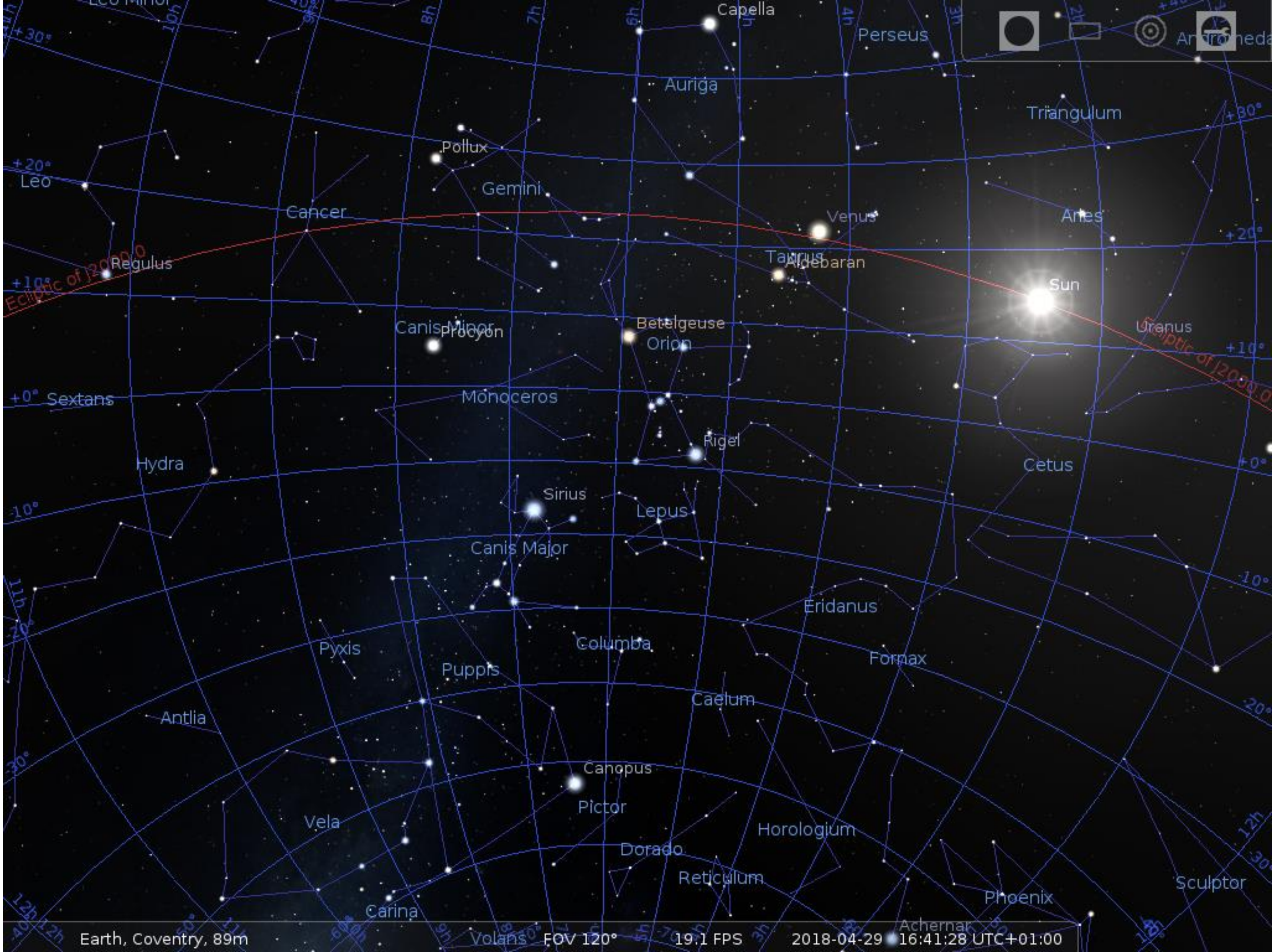
Sun on April 29, 2018, looking towards vernal equinox.

North is up; the Sun moves to the left and is moving North at the moment.



Same time, looking towards point of summer solstice (RA=6, Dec=+23)

Images made with *“stellarium” (free software)*



Moon & planets also near ecliptic

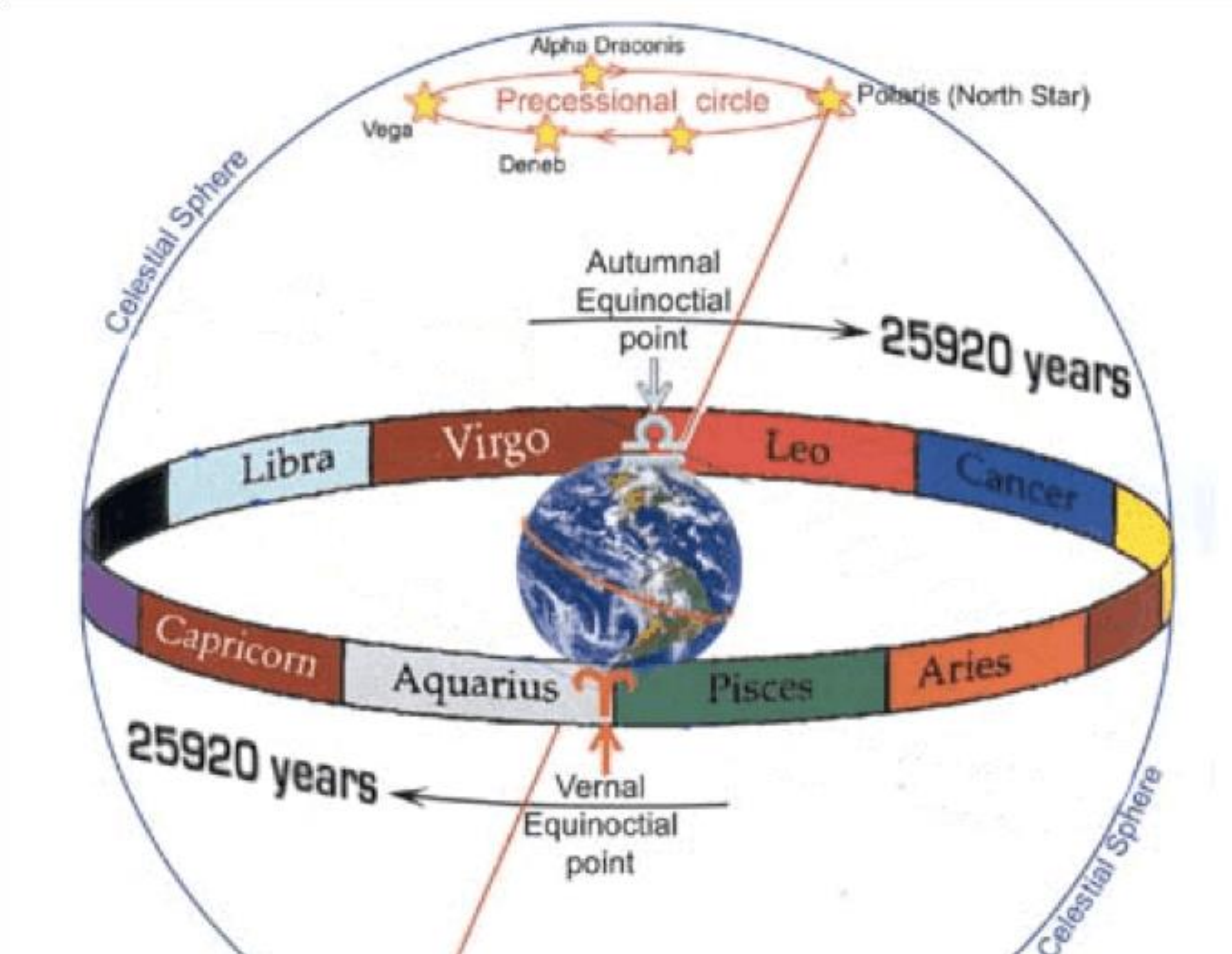
Atel 11448, 20 March 2018:

*"Peter Dunsby (University of Cape Town) reports the detection of a **very bright optical transient** .... The object was ... **not seen when this field was observed previously** .... **The optical transient is at least first magnitude** and is located at the following coordinates:* RA (2000): 18h 04m 50s Declination (2000.0): -23d 29m 58s ..... *Further observations are strongly encouraged to establish the nature of this very bright optical transient."*

First Galactic SN since Kepler 1604?!? ..... or Mars ......

Precession of the Equinox

- Earth's axis ***precesses*** around its orbital axis due to tides from Sun & Moon once per 26,000 years.
- The north pole is constantly wobbling in a circle. Polaris is currently the ***pole star*** but for the Romans (~2000 years ago), other stars were closer to the pole.

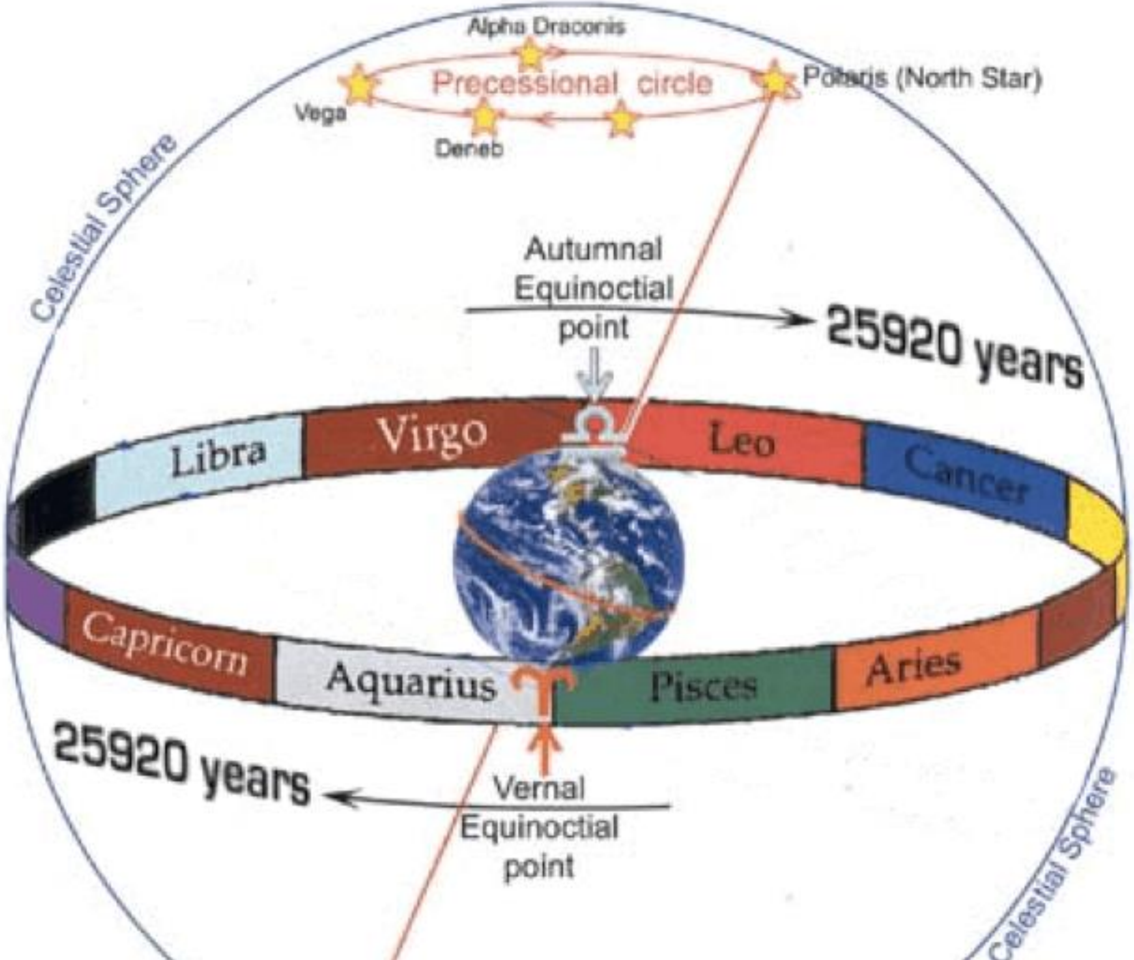


Precession of the Equinox

- RAs, Decs of celestial objects vary with time.
- Therefore, need to specify date ("B1950.0", "J2000.0").
- For example, position of quasar 3C 273:

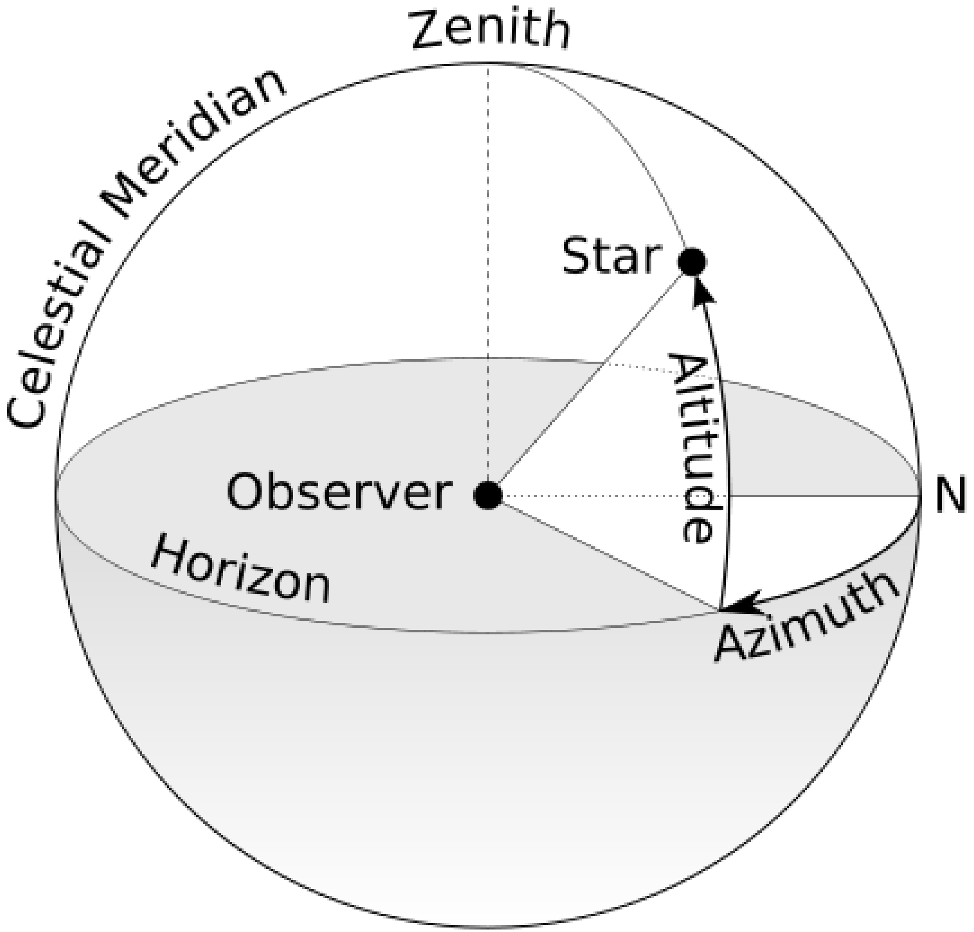
RA = 12 29 06.70,
Dec = +02 03 08.7 (J2000)

RA = 12 26 33.28,
Dec = +02 19 43.1 (B1950)



Azimuth & Elevation

- RA & Dec are equatorial coordinates.
- When observing, the position on the sky is measured by ***azimuth*** and ***elevation*** (also known as ***altitude***, hence ***alt/az***)



Bluff your way in Observing

- ***Meridian***: imaginary line running North-South. Objects reach their maximum elevation on the meridian ("transit" or "culmination")
- ***Zenith***: point directly above observer (elevation = 90°)
- ***Zenith distance (z)***: angle measured from zenith (90-elevation)
- **Airmass (*X*)**: amount of atmosphere one is looking through relative to the zenith [~ sec(z)].
- ***Hour angle (h)***: hours since object crossed the meridian.
- ***Local Sidereal Time (LST)***: RA of object on meridian

RA, Dec to Alt, Az

- Right ascension, hour angle and LST are linked:

  hour angle, $h = LST - RA$

- ***h***, the observer's latitude, ***l*** and the declination, ***δ*** are enough to determine the azimuth, ***a*** and elevation, ***e***. There are some unmemorable formulae for this:

$$\cos(e)\cos(a) = \cos(l)\sin(\delta) - \sin(l)\cos(\delta)\cos(h)$$

$$\cos(e)\sin(a) = -\cos(\delta)\sin(h)$$

$$\sin(e) = \sin(l)\sin(\delta) + \cos(l)\cos(\delta)\cos(h)$$

but use astropy.coordinates (Python) or equivalent!!

Stellarium

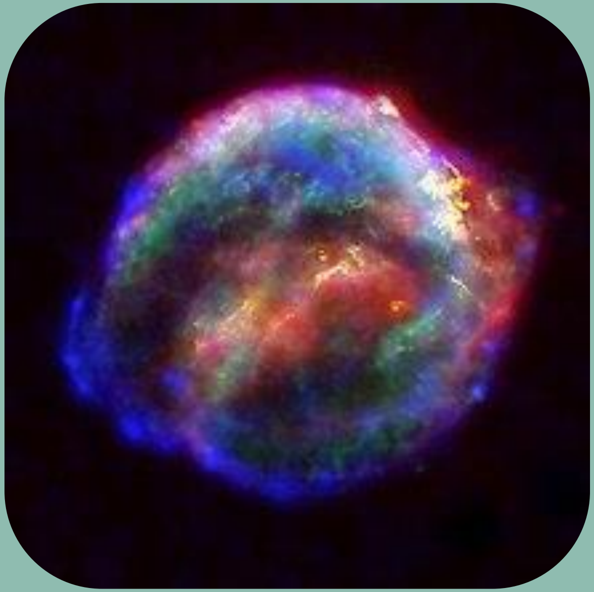
- Free software usually used by amateurs or for general interest.
- Web version is simpler but easy to use without needing downloads
- Automatically calculates precession, as well as RA and Dec and Alt/Az for a given time and observing location
- Includes atmosphere etc.
- Good for building intuition about how the sky moves.

https://stellarium.org/
https://stellarium-web.org/

Activity

We're going to look at Kepler's Supernova:

- Location: 17h 30m 42s -21deg 29m
- Date: 8th October 1604
- Observed from: Prague, visible for 18 months

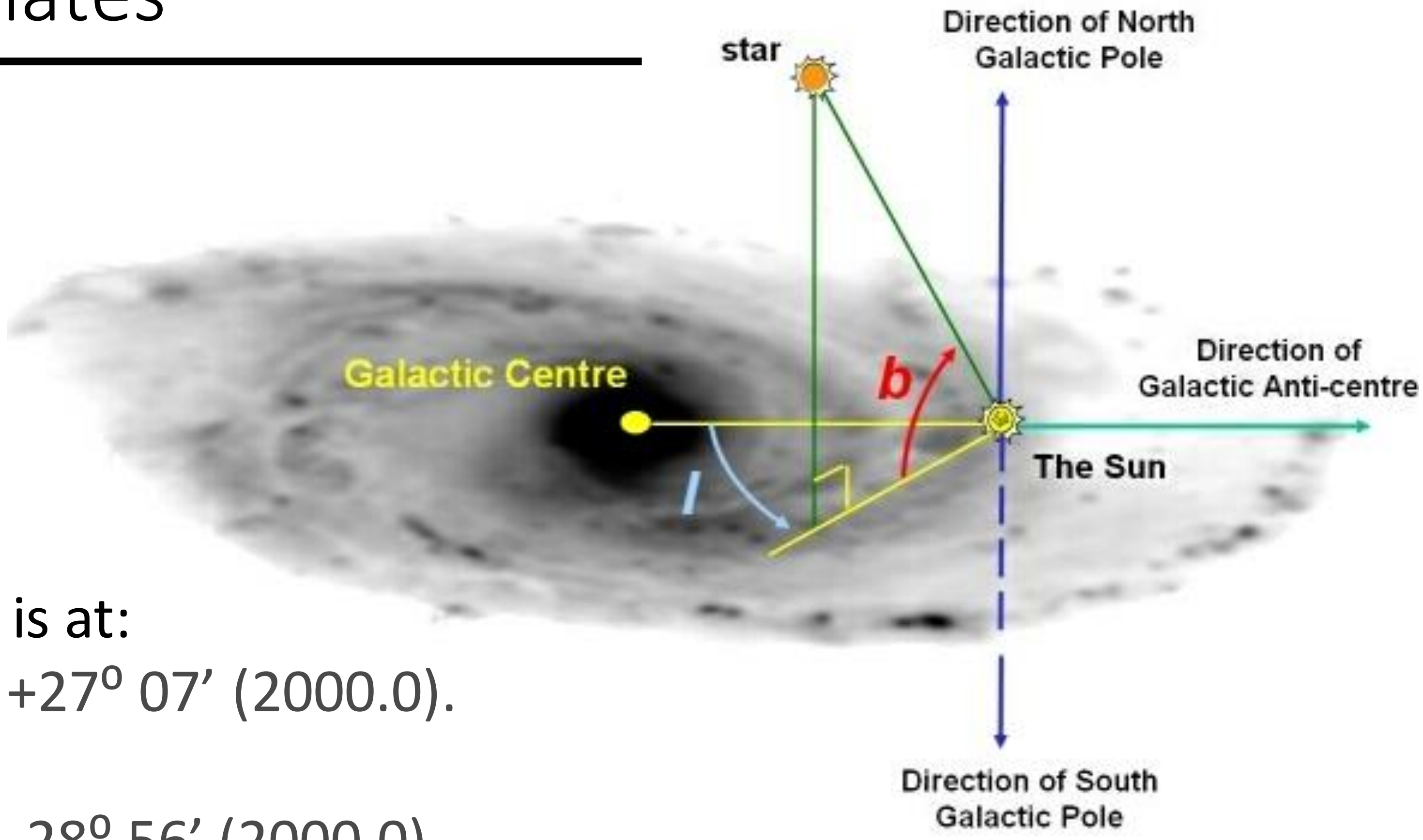


Consider this event using Stellarium.

1. What direction was Kepler looking?
2. At what time of night?
3. What else was nearby in the sky?
4. What challenges did he face?
5. How did observability change over time?

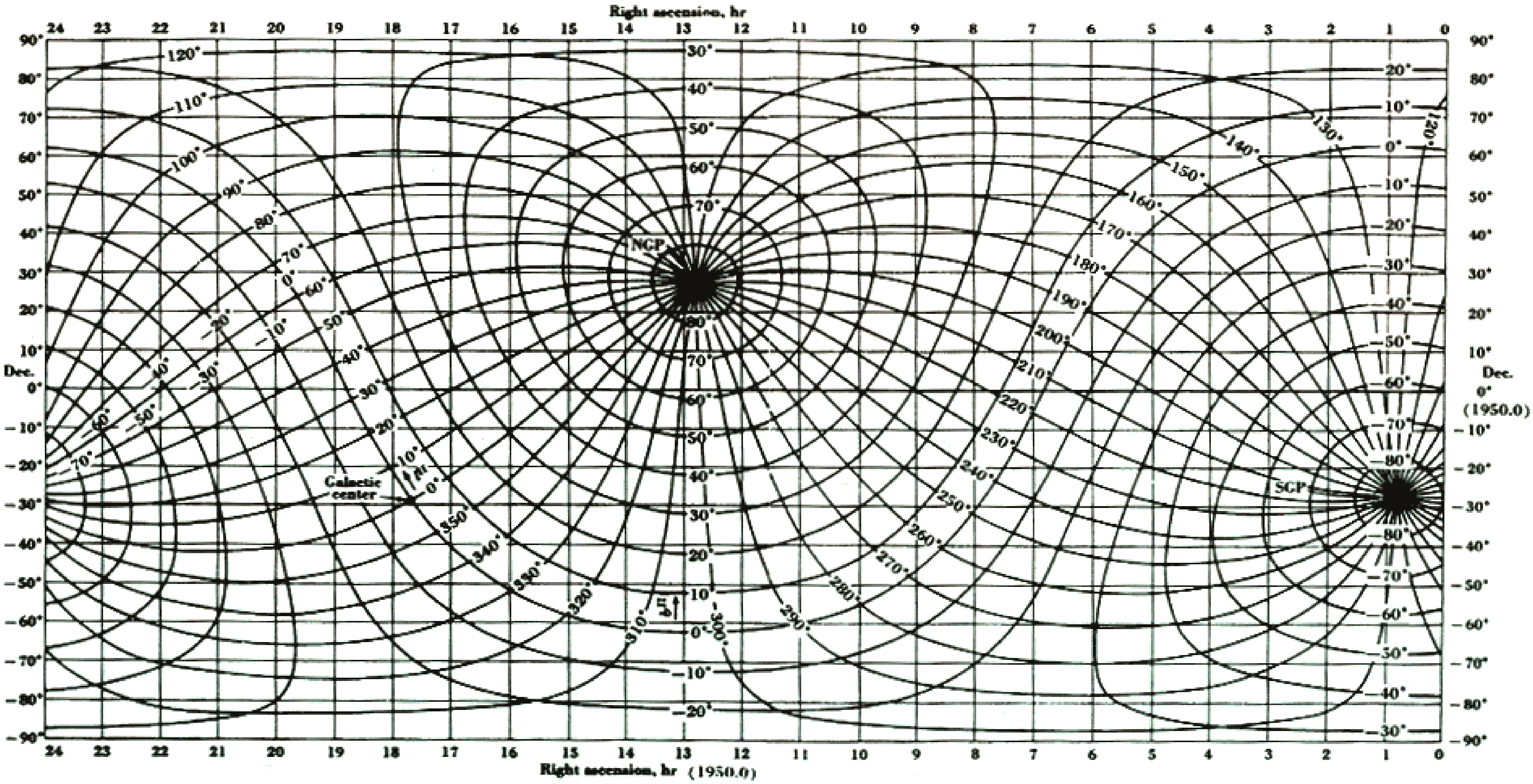
Galactic Coordinates

Galactic longitude = l
Galactic latitude = b



The galactic north pole is at:
RA = 12h 51.4m, **Dec** = +27^o 07’ (2000.0).
The galactic centre at:
RA = 17h 45.6m, **Dec** = -28^o 56’ (2000.0).
The ***inclination*** of the galactic equator to Earth’s equator is 63^o.

https://astronomy.swin.edu.au/cosmos/G/Galactic+Coordinate+System



http://egg.astro.cornell.edu/alfalfa/grads/set5.htm

ICRS

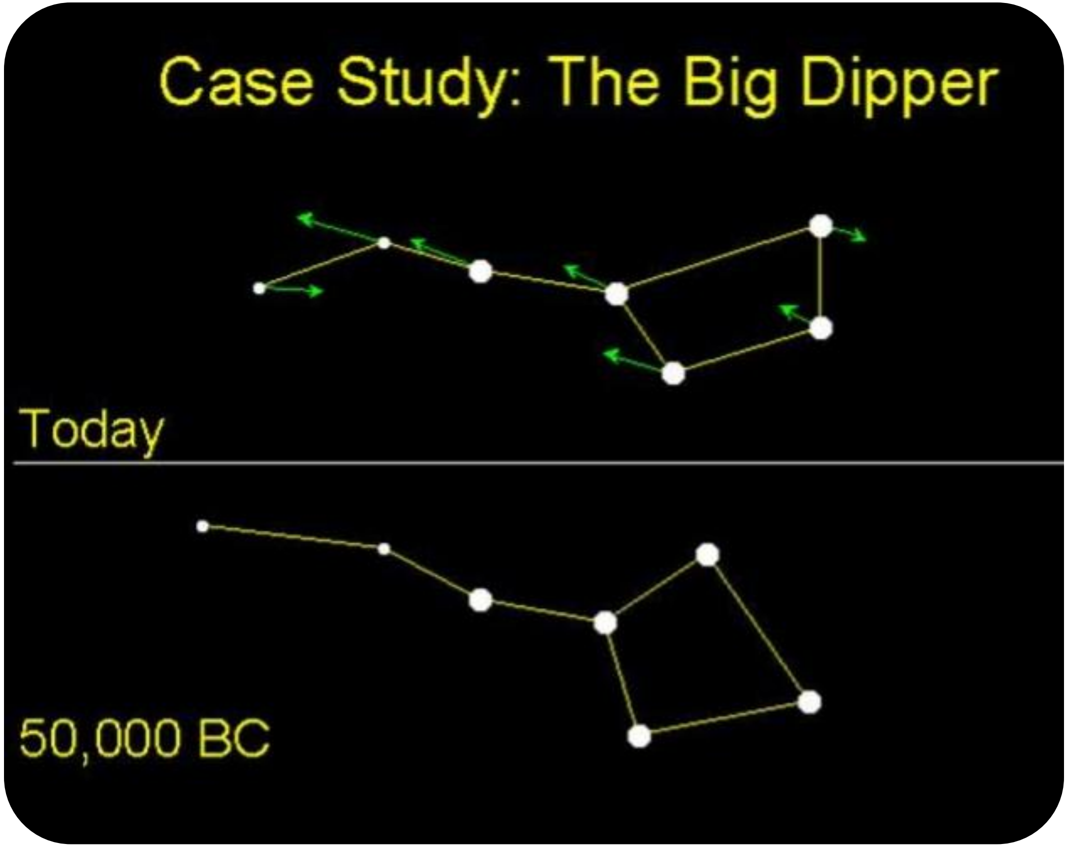
- ***International Celestial Reference System (ICRS)***: fixed reference frame defined by distance objects (QSOs).
- Defined to be close to J2000 equinox coordinates.

FUN FACT

Precession is why the constellations of the zodiac, beloved of astrologers, are not quite right. For example, you could be a Scorpio, but the Sun was in Libra when you were born – whoops.

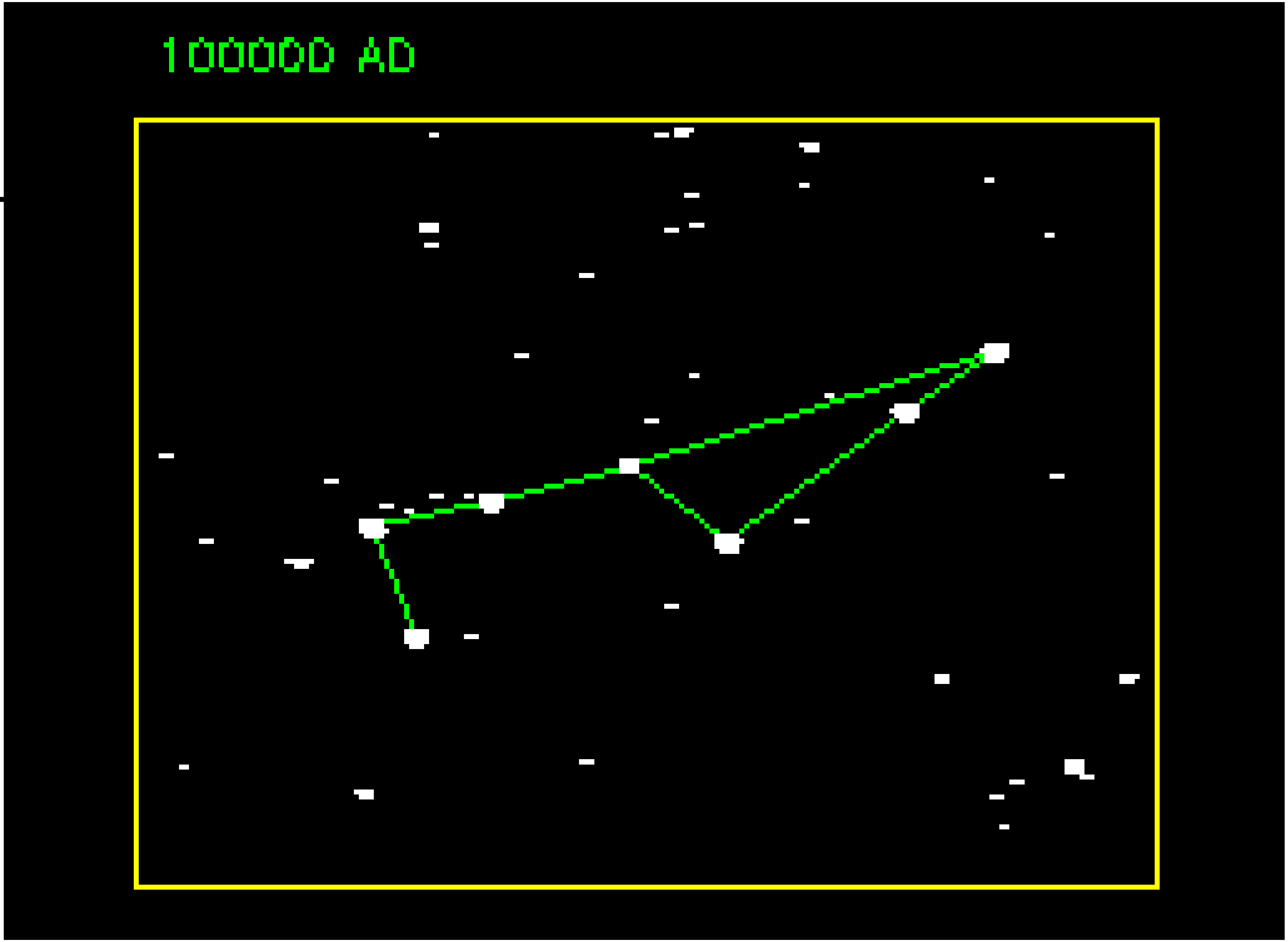
Proper Motion

- Objects (especially if nearby) can genuinely change position. This is called ***proper motion***.
- For example, Gaia DR3 lists ***pmra*** and ***pmdec*** (with errors) in mas/yr (milliarcseconds per year).
- Given proper motion, one needs to define the ***epoch*** of coordinates For example, in Gaia DR2 epoch is J2015.5 and for DR3 J2016.0



Proper Motion

http://www.astronomy.ohio-state.edu/~pogge/Ast162/Movies/proper.html



Proper motion: beware!

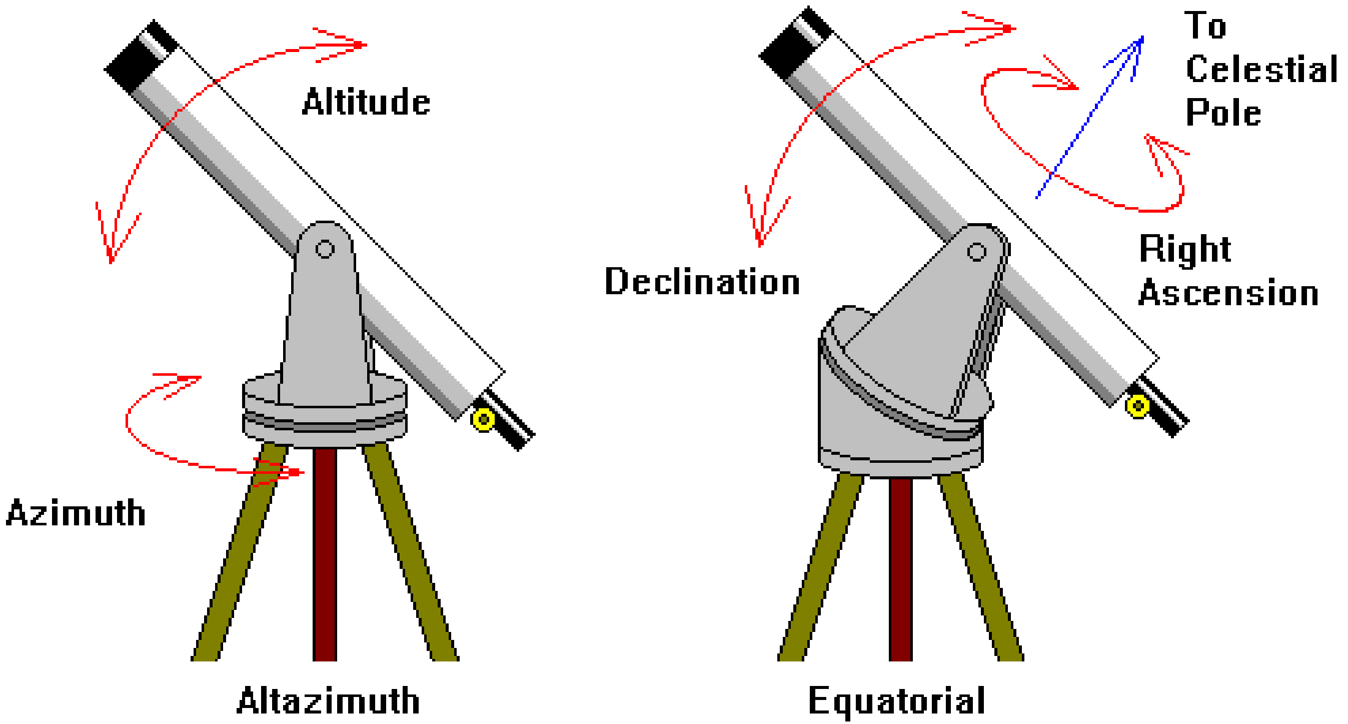
- Some telescopes may require RA proper motions in ***seconds of RA per year***.
- Note: 1 second of RA ≠ 15”
- Instead: 1 second of RA = 15” cos(δ)
- Important to check for proper motion in targets ***and*** alignment of reference stars

Useful Resources

- SIMBAD – for finding data on known/bright objects: http://simbad.u-strasbg.fr/simbad/
- NED – equivalent, maybe slightly better for extragalactic objects: https://ned.ipac.caltech.edu
- DSS – the digitized sky survey: useful for making “finding charts”: https://archive.stsci.edu/cgi-bin/dss_form (but beware proper motion)
- Gaia Archive – astrometry, photometry, and spectroscopy of nearly 2000 million stars in the Milky Way: https://gea.esac.esa.int/archive/

Equatorial vs Alt-Az Mounts

- ***Equatorial*** mount are mounted with one axis parallel to Earth's axis. As a result, only need to rotate one axis to track stars.



- ***Alt-Az*** mount have a vertical & horizontal axis. This is easier engineering-wise for large telescopes. However, both axes are needed to track stars and the field needs to be de-rotated.

ESO 3.6m – Equatorial

- Is the telescope pointing North or South?
- (ESO 3.6m is sited at La Silla, Chile)

WHT 4.2m – Alt-Az

- Alt-Az telescopes struggle to track near the zenith when azimuth changes rapidly.
- De-rotation can hit end-stop in the middle of an observation (annoying).
- All largest telescopes are alt-az.

Rule of Thumb One

Can typically access targets with RAs opposite to the Sun, +/- 6 hours or so.

- Which are [in principle] observable tonight from the UK?
- If they are, are they best observed at the start, the middle or the end of the night?

1. RA = 11:30, Dec = +85:30
2. RA = 19:50, Dec = +20:20
3. RA = 06:20, Dec = -10:00
4. RA = 03:55, Dec = +55:00

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Sun is at 14h -12deg. At midnight, the Local Sidereal Time (LST) will be 2h29.

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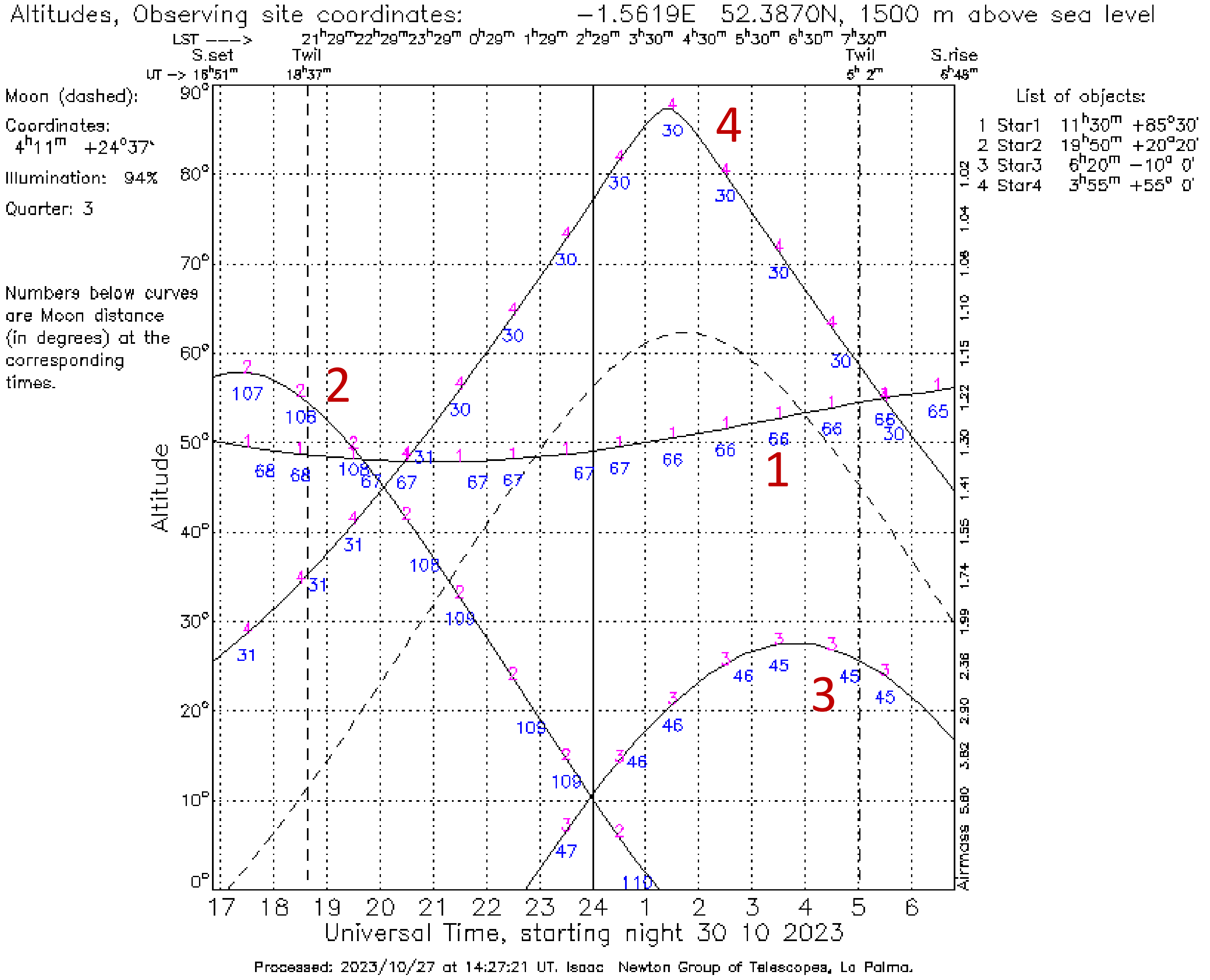
Sun is at 14h -12deg. At midnight, the Local Sidereal Time (LST) will be 2h29.

1. RA = 11:30, Dec = +85:30 ***Daytime Object***
2. RA = 19:50, Dec = +20:20 ***Twilight***
3. RA = 06:20, Dec = -10:00 ***Near Horizon***
4. RA = 03:55, Dec = +55:00 ***Observable***

Nowadays, the easiest way to do this is to use online or software calculator. (Thank goodness for computers!)

See: http://catserver.ing.iac.es/staralt/



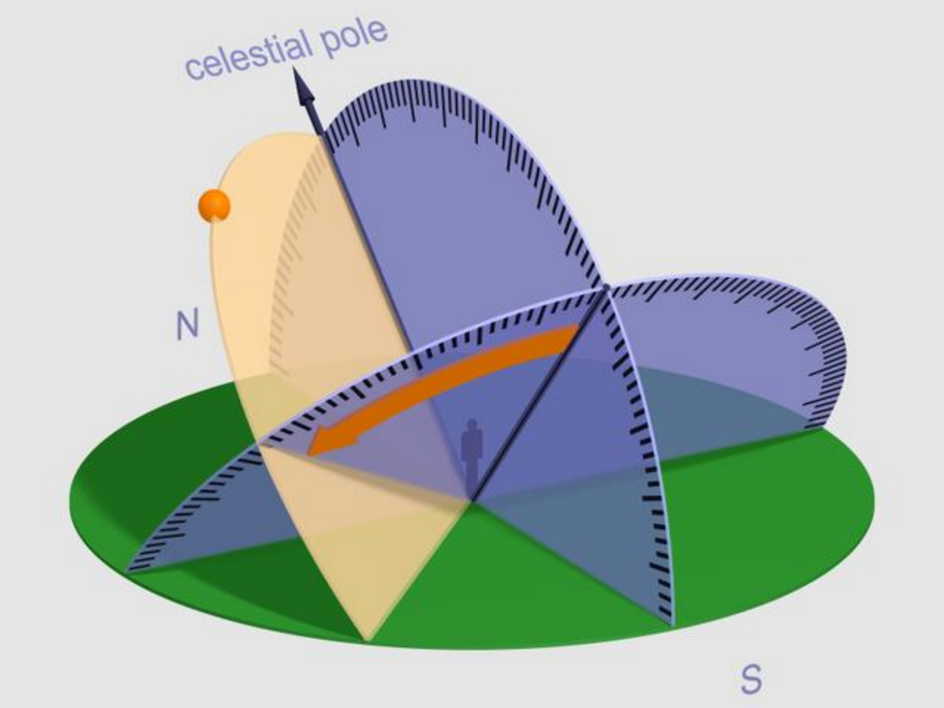
Rule of Thumb Two

- The ***hour angle (h)*** is really useful at the telescope.
- It is the time until (East) or since (West) a star crosses or has crossed the meridian.

$$h = LST - RA$$

with h ~ 0, or RA ~ LST.

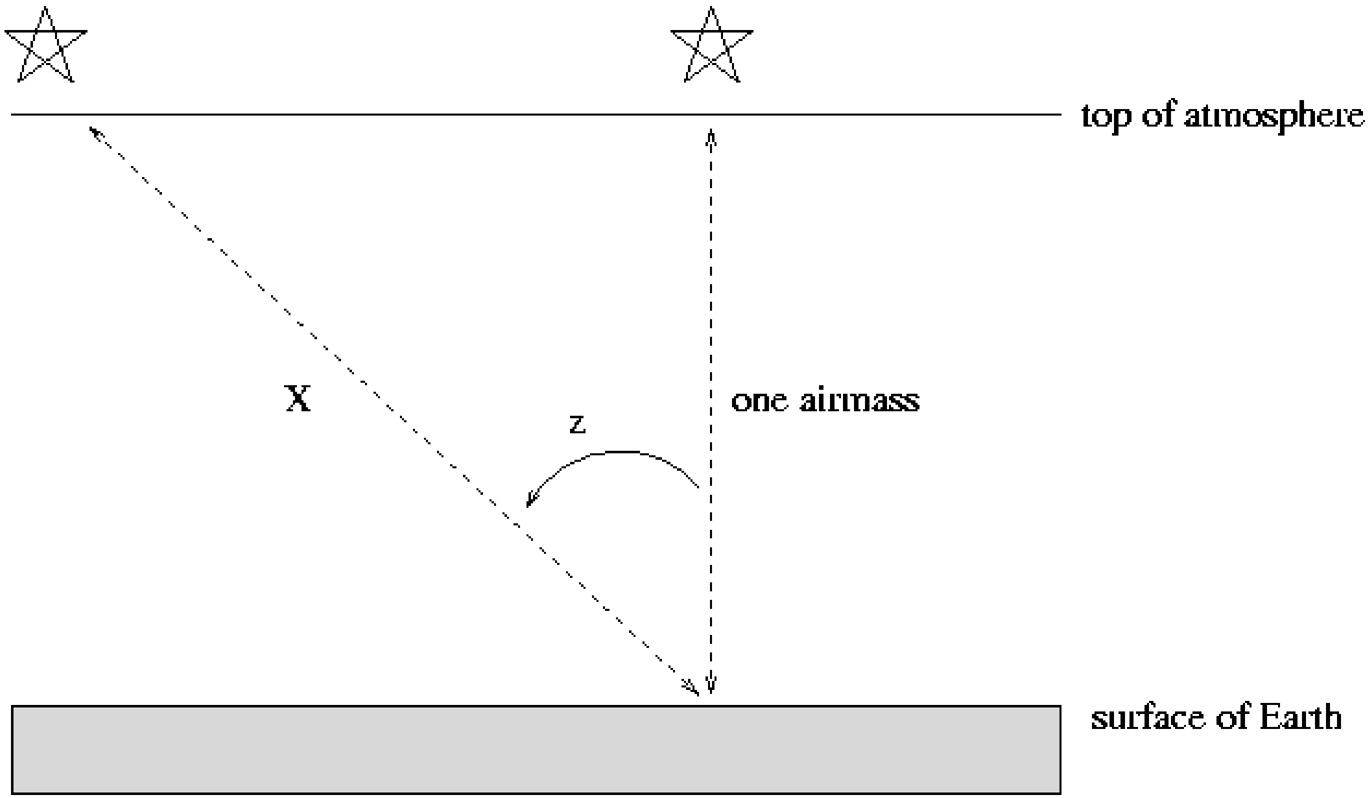
- Observatories often display the LST.
- Objects of larger RA rise later in the night (Note: 01 > 23 in RA-land)



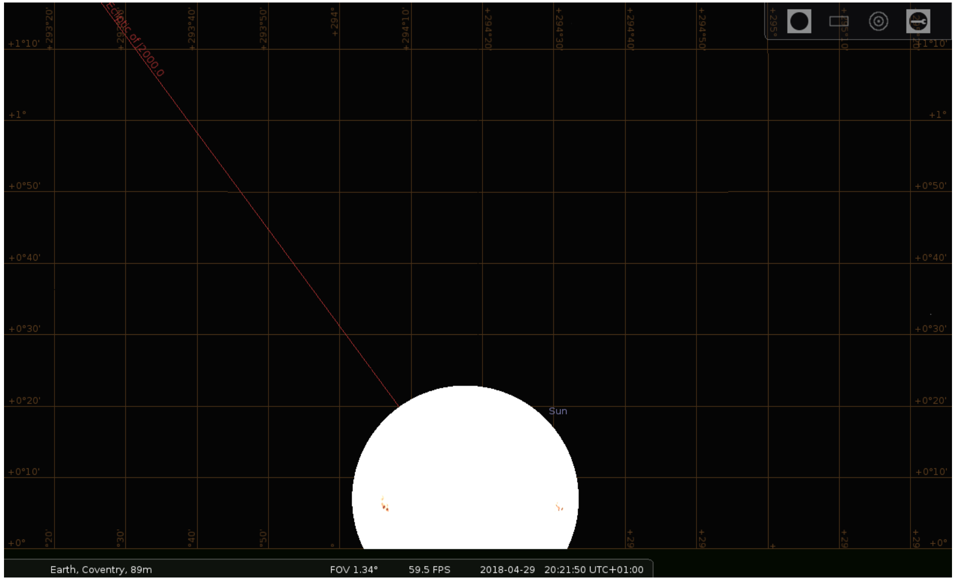
Rule of Thumb Three

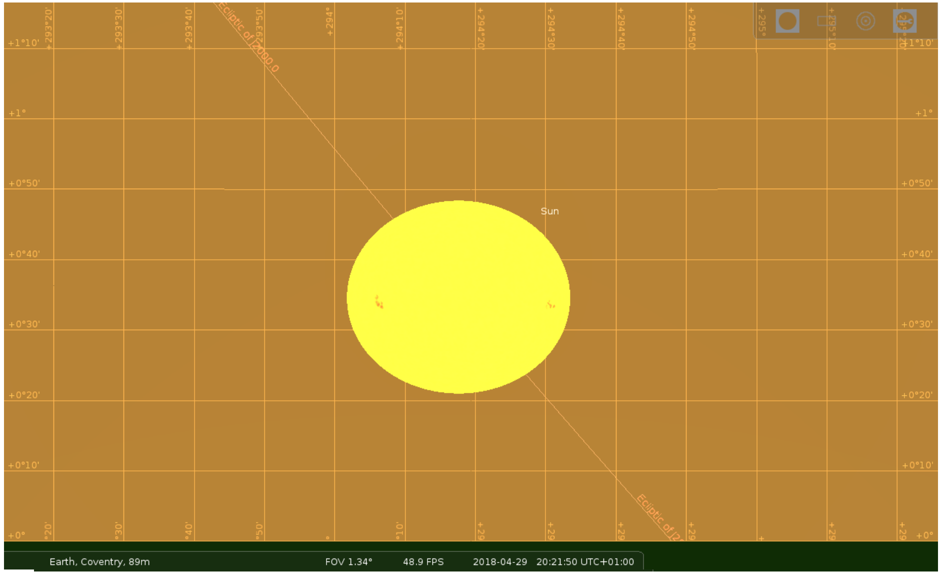
- Don't, if you can avoid it, observe at zenith distances > 60° (which is ***airmass*** > 2)

- **Never** observe at zenith > 70°
  The light is struggling through 3 atmospheres!



Refraction

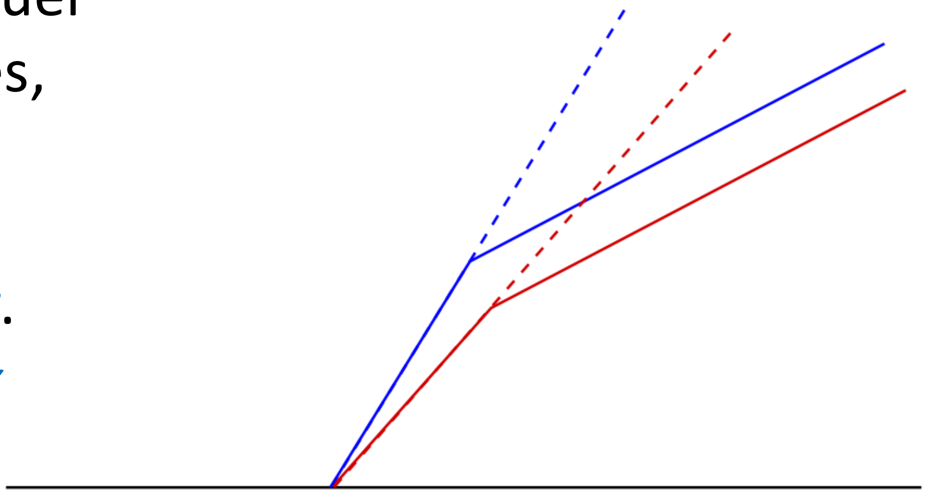




Same time near sunset, Coventry, April 29, without (left) & with (right) an atmosphere (according to “stellarium”)

Differential Refraction

- Refractive index increases towards bluer wavelengths. At large zenith distances, objects turn into mini, ***vertical rainbows***.
- Makes astrometry ***colour-dependent***.
- Leads to ***wavelength-dependent flux loss*** in spectroscopy
- If no ***ADC*** (atmospheric dispersion corrector) observe near zenith and use a ***vertical slit***.
- *Classic paper: Filippenko (1982, PASP)*

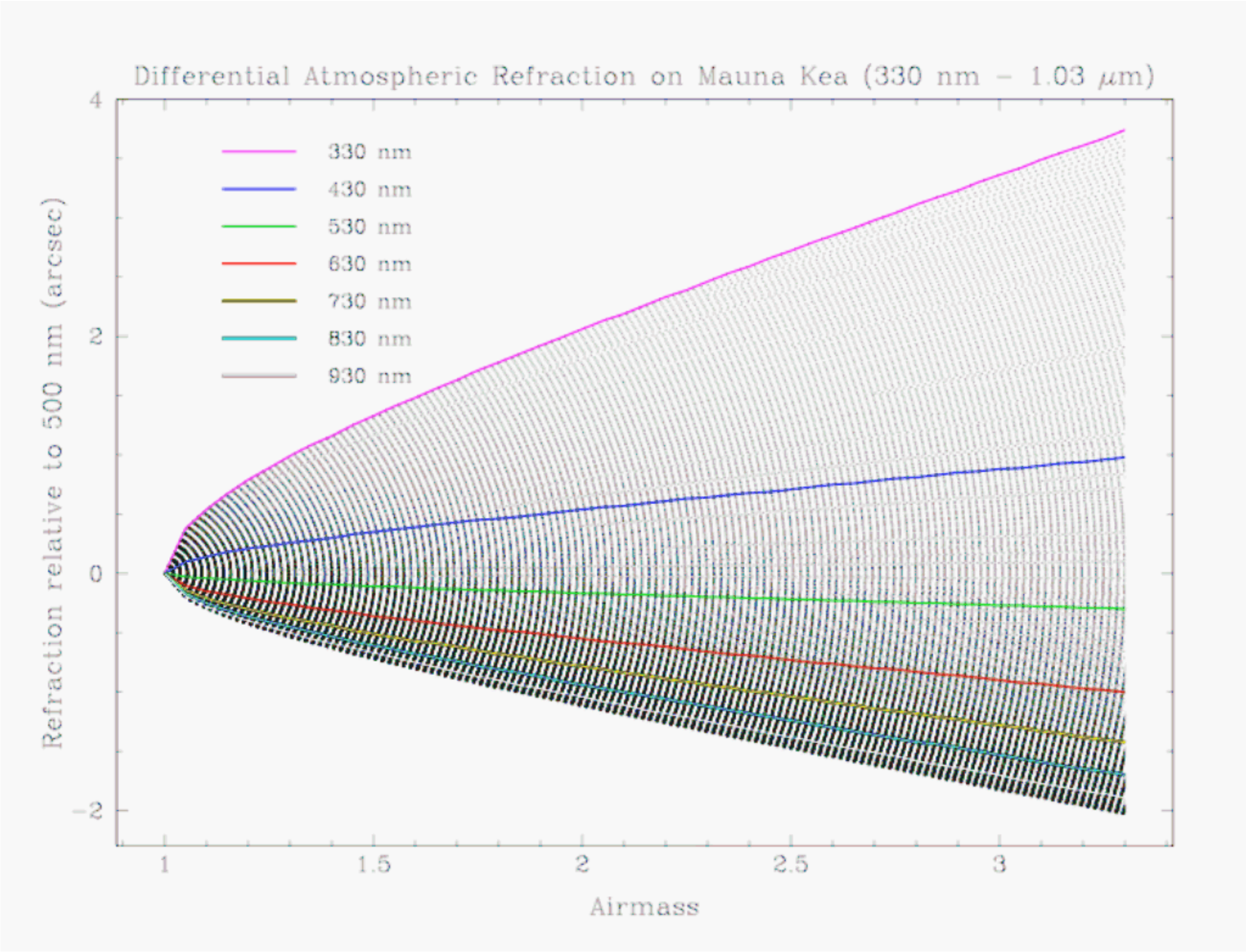


https://ui.adsabs.harvard.edu/abs/1982PASP...94..715F/abstract

Typical slit widths are 0.7” to 1.2” on the sky (see later). Fibres tend to be 2” to 3”.

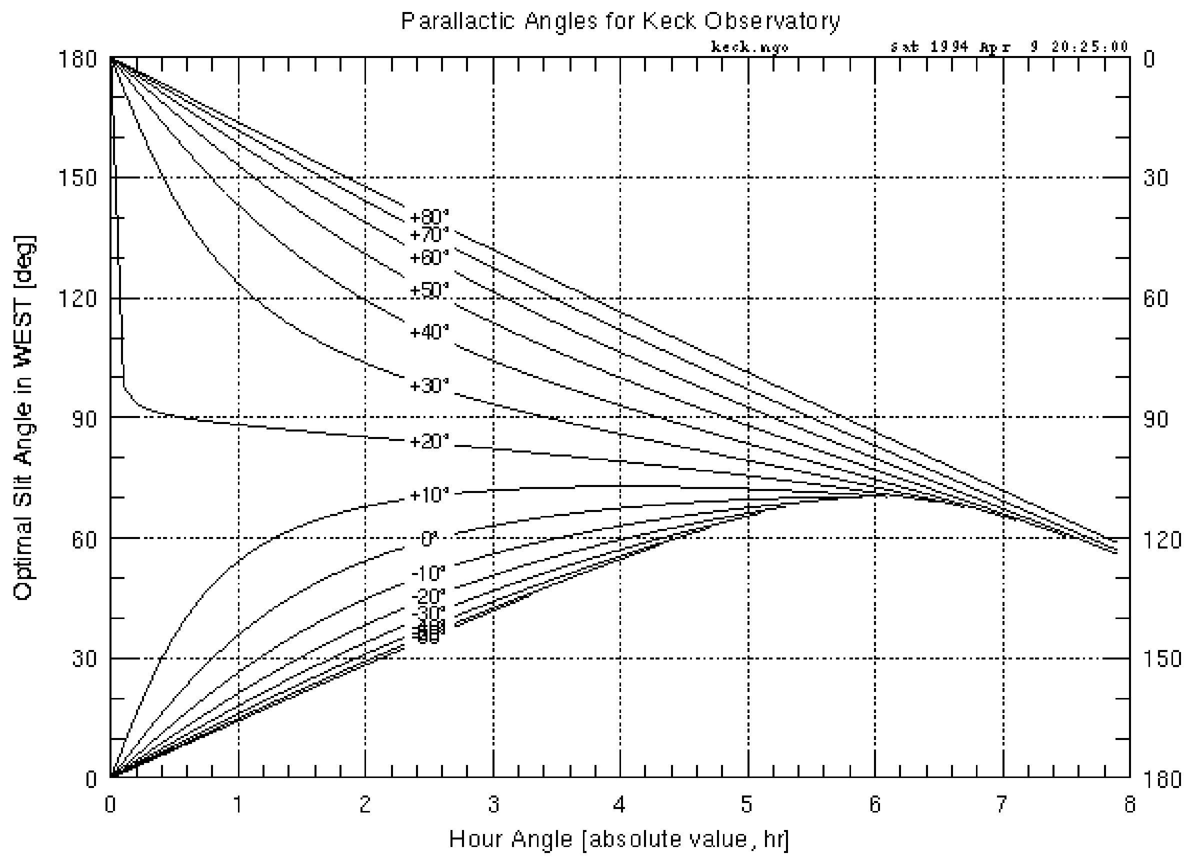
Differential refraction can be very significant, especially in the ultra-violet.

BE AWARE OF IT FOR OPTICAL SPECTROSCOPY!



The ***parallactic angle*** measures the direction from the target to the zenith.

Light is dispersed in this direction because of terrestrial atmospheric refraction. If the slit is not aligned to the parallactic angle, then certain wavelengths of light will fall outside the slit.



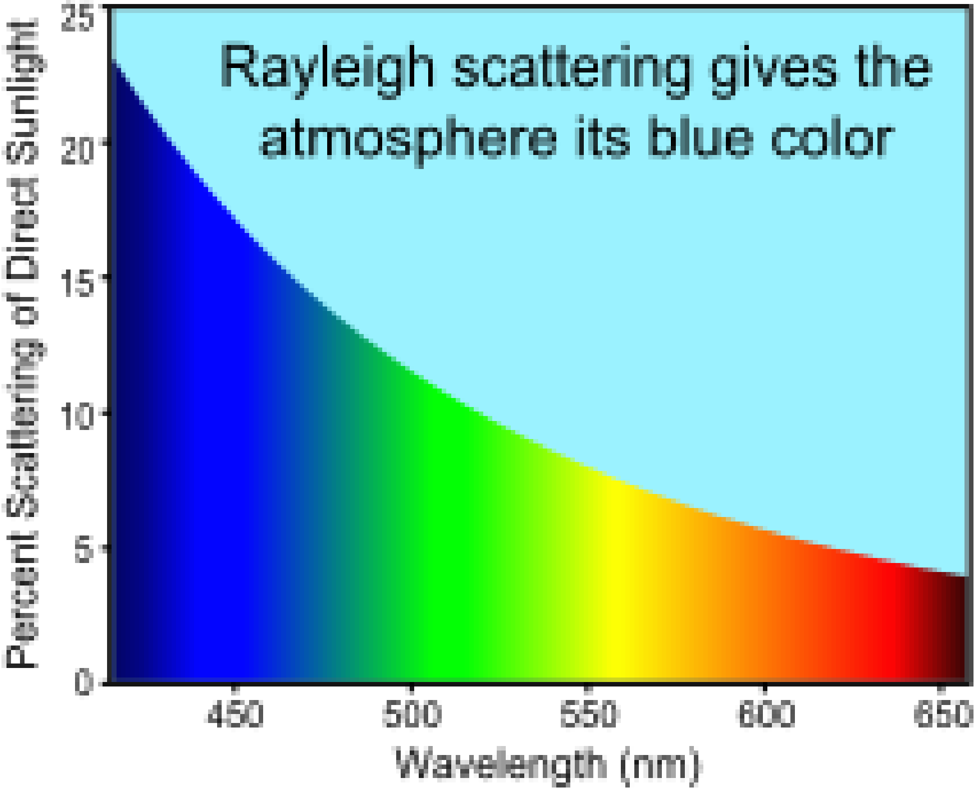
https://www2.keck.hawaii.edu/inst/common/parallactic.html

Atmospheric Extinction

- Earth's atmosphere absorbs and scatters light.
- The effect is worst at short wavelengths (Rayleigh scattering).
- Extinction makes stars fainter according to:

$$m(X) = m_0 + k\,X$$

where X is the ***airmass***, m the ***magnitude,*** k is the ***extinction coefficient***, measured in mags/airmass.



Atmospheric Extinction

Example coefficients:

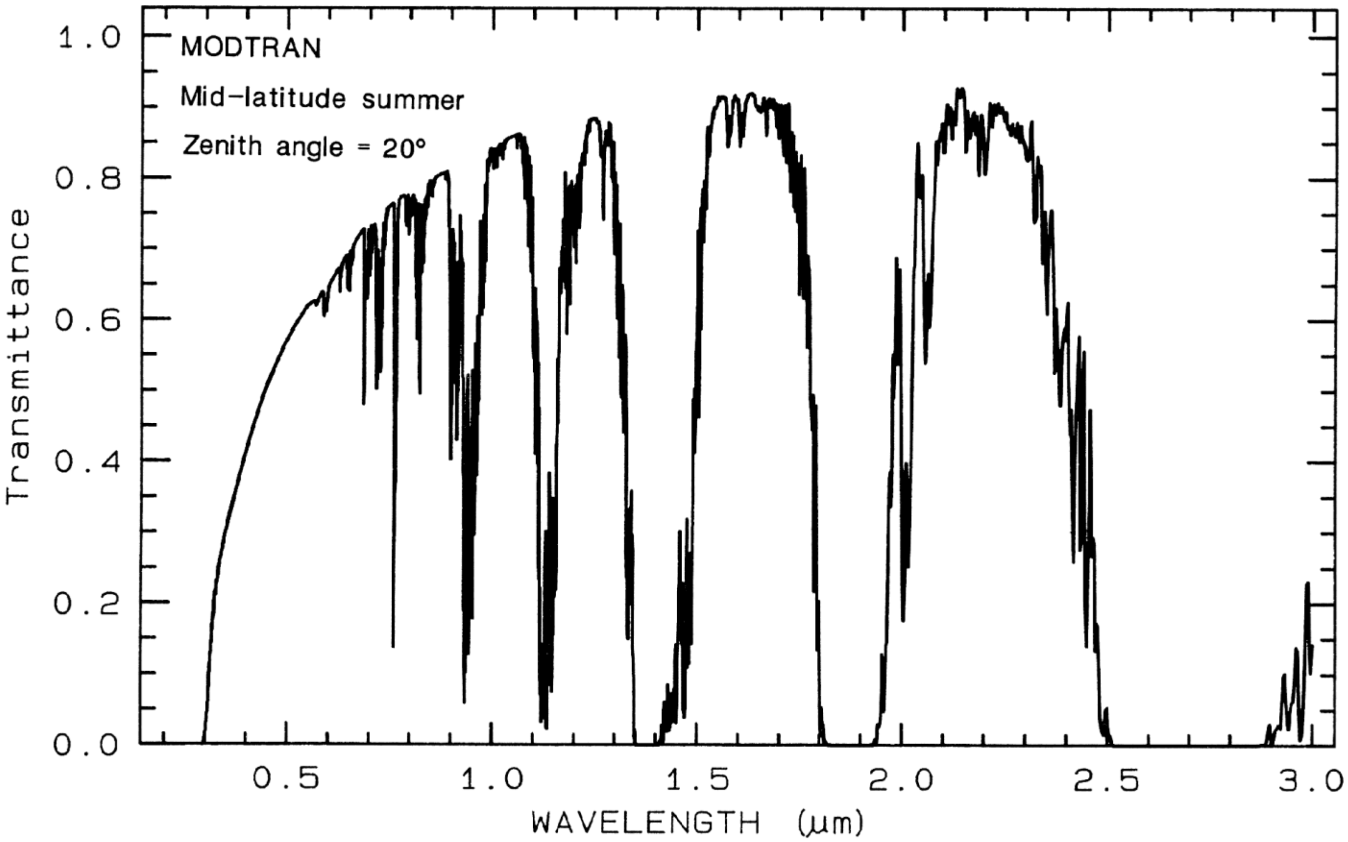
La Palma: $k_r = 0.069$, $k_g = 0.161$, $k_u = 0.485$

Purple Mountain: $k_r = 0.55$, $k_g = 0.70$

Extinction varies from site to site, and day to day. Measuring it requires observation over a wide range in airmass. Often easier to use measured mags for stars in the field than to try to derive from standard stars at other locations.

Atmospheric Extinction

- Smooth Rayleigh scattering dominates the blue end of optical.
- ***Molecular bands*** appear at longer wavelengths.
- So strong that they define observing bands, e.g., the near-infrared H & K bands at ~1.6 & 2.2 microns



Sky Brightness

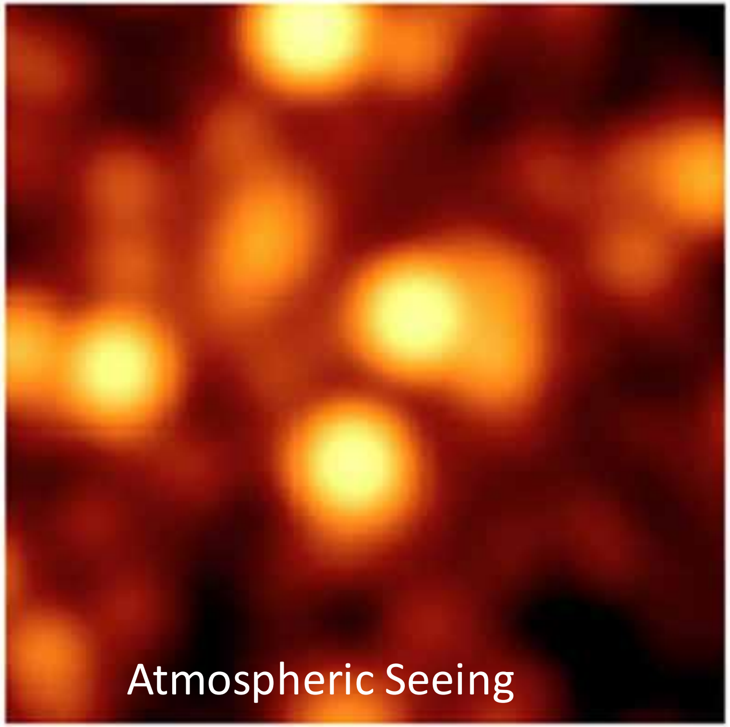
- Sky background is a crucial component of observing.
- Usually measured as an ***equivalent magnitude per square-arcsec***.
- Typical dark site: V=21.9 (dark time, no Moon), rising to ~18 during Full Moon.
- Brighter, but less affected by the Moon in the infrared.

Seeing

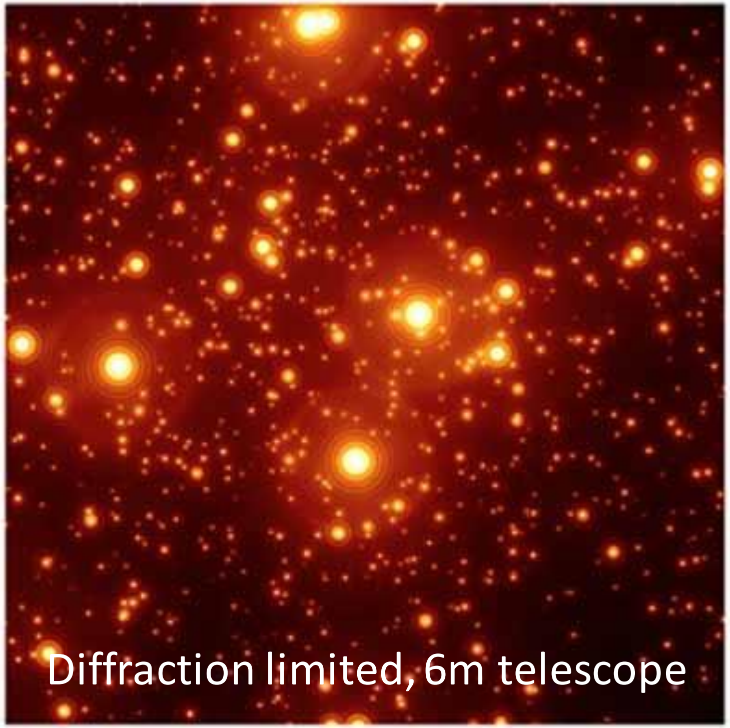
- A telescope of aperture 12 cm has a diffraction-limited angular resolution of $1.22\,\lambda/D$ = 1.04”
- Unfortunately, a 12 m telescope is not necessarily any better because of ***seeing***, the absolute bane of ground-based optical / infrared astronomy.

Seeing

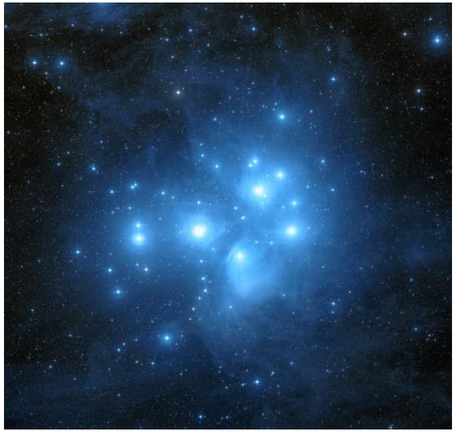
- Seeing is often worse than 1 or 2”.
- The best sites sometimes have a seeing ~ 0.3”. Better than this requires ***adaptive optics*** or space to reach the diffusion limit.



Atmospheric Seeing



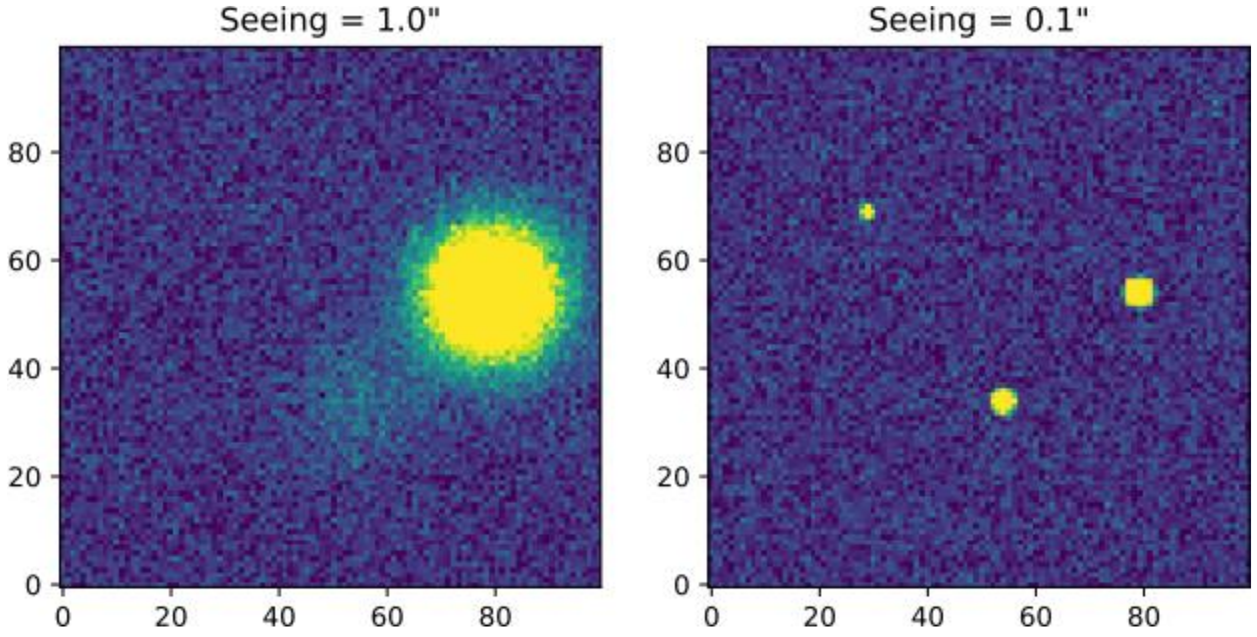
Diffraction limited, 6m telescope



Hubble observations

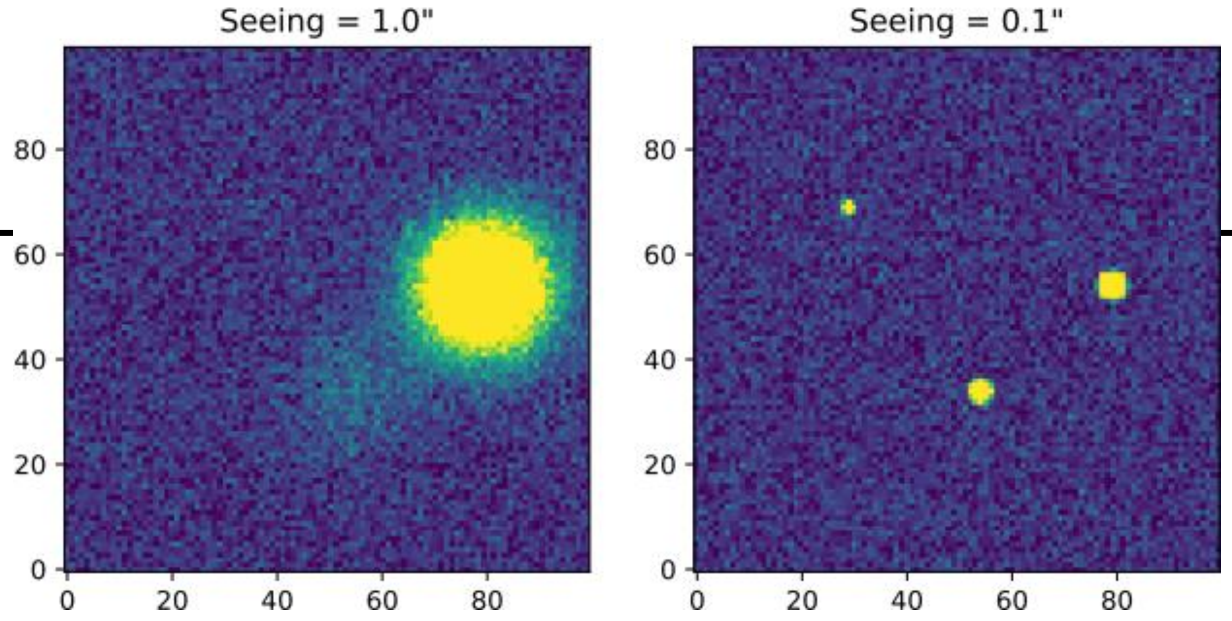
Faint Object Detection

Seeing is crucial for faint object detection and is the reason why the 2.4m Hubble Space Telescope can still beat much larger ground-based telescopes.



Faint Object Detection

- The faintest object has 1000 photons on top of a background of 100 photons per 0.05” pixel.
- Let’s estimate the ***signal-to-noise ratio*** in a circle of radius = 2****seeing***:



N(pixels) = π(2*seeing/0.05)^2

Seeing = 1.0”, therefore, N(pixels) = 5000

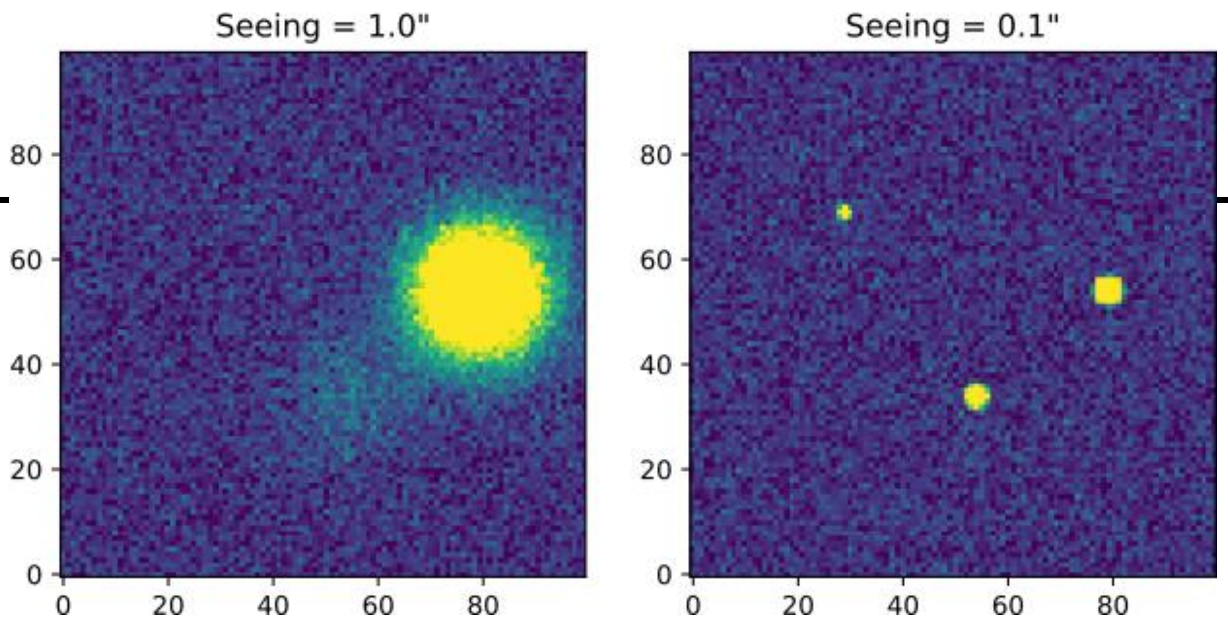
Total sky counts = 5000*100 = 500,000

Total counts = 501,000

Assuming Poisson statistics: noise = sqrt(501,000) = 708

SNR = 1000/708 = 1.4 (***no detection***)

Faint Object Detection



For seeing = 0.1”:

N(pixels) drops by 100 times

Therefore, total counts = 6000

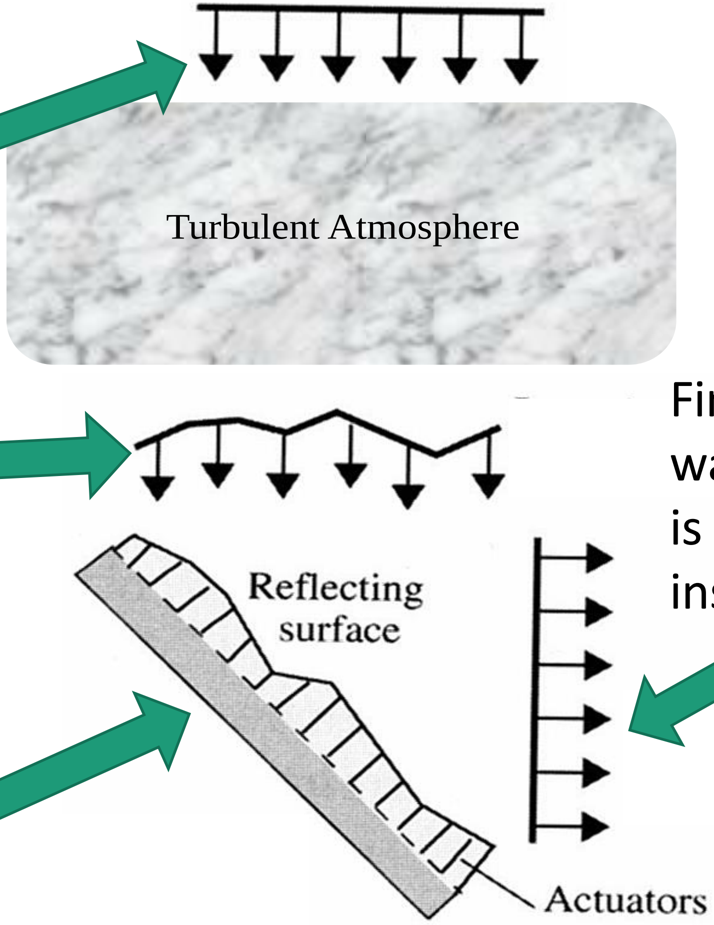
SNR = 1000/sqrt(6000) = 12.9 (***convincing detection***)

Adaptive Optics (AO)

Light travels from distant objects.

Light is distorted by the Earth's turbulent atmosphere and arrives at the telescope as an incoming distorted wavefront.

The level of distortion on the incoming wavefront is measured and actuators are adjusted to distort the mirror and compensate for this.



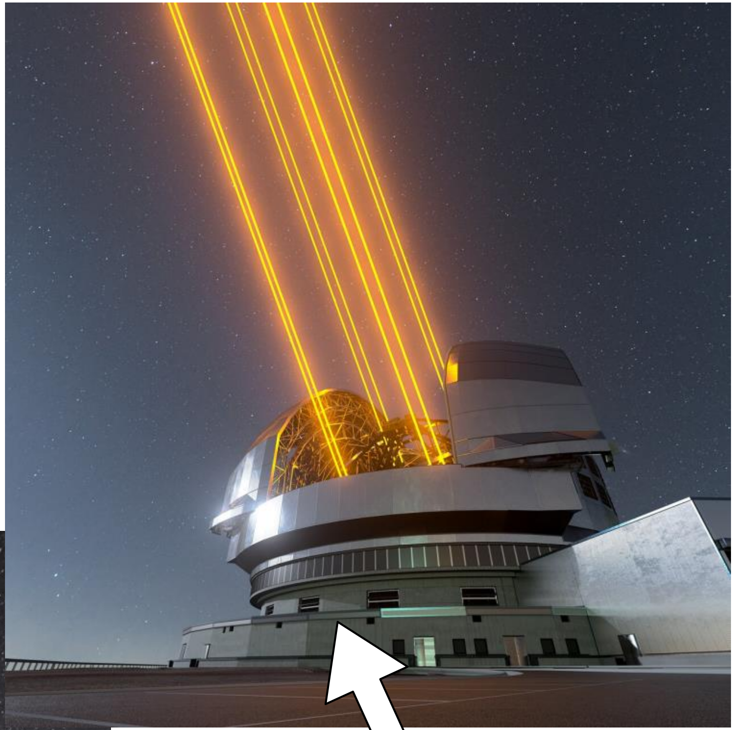
Final corrected wavefront which is sent to instrumentation.

Adaptive Optics: How is it done?

- **Guide stars**: must be bright (<12th mag) and close to target (within telescope field). Can be natural or a pocket of sodium atoms excited in the upper atmosphere by lasers.
- **Wavefront sensor**: measures distortion of the guide star at kHz frequencies.
- **Deformable mirror**: optical element distorted by actuators that respond to the wavefront censor to correct the wavefront.
- **Multi-Conjugate AO** (MCAO): using several guide stars to correct a larger field.
- **Strehl ratio**: The degree of correction
  S = (observed peak intensity)/(diffraction limit theoretical peak intensity)

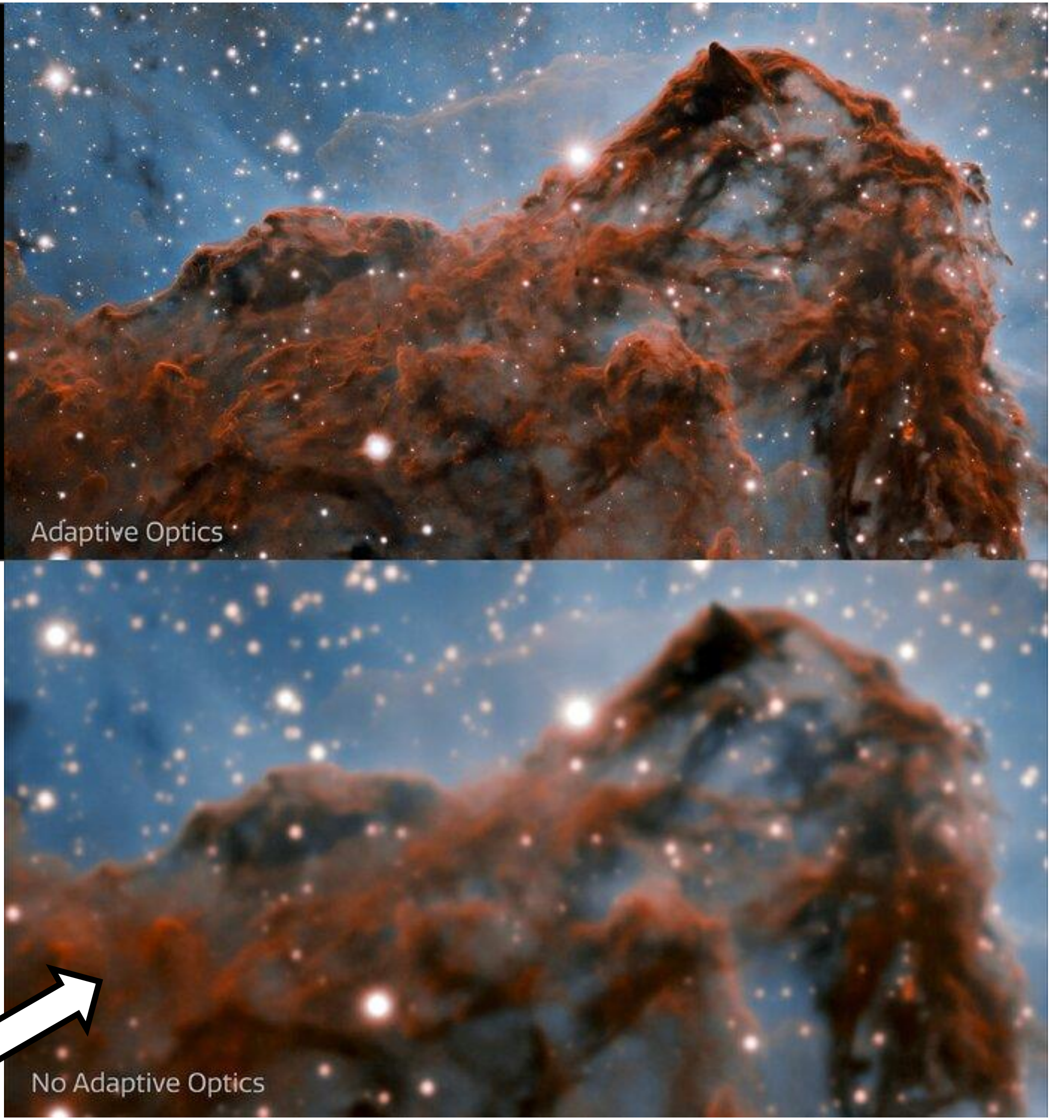
Laser Adaptive Optics in Action

The Very Large Telescope (VLT) in Paranal, Chile.



The Extremely Large Telescope (ELT), first light in 2028.

Neptune imaged with MUSE on the VLT in Chile.



Some points to note:

- Correction easiest in the near-infrared
- Corrected images often show the Airy disk around sources.

Western wall of the Carina Nebula taken by the international Gemini Observatory in Hawaii.

Astronomical Timescales

- Humans have been using the motions of the stars, Sun, and Moon for thousands of years to regulate their hunting, crops, religion, and lives in every way.
- In astronomy, particularly for observations, measuring time including its precision is extremely important.
- The complexity of time really increases with precision.
- If you do any work on time-variable objects you will come across ***Julian Date*** (and its many modified forms), ***Universal Time***.
- **Many have been burned by one or more of these.**

Julian Date (JD)

- Number of days since ***midday on January 1st, 4713 BC (not same as Julian calendar)***

For example:

30th October 2023 at 2:00pm is

JD= 2460248.083333

JULIAN DATE CALENDAR 2023

Day	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1	1	32	60	91	121	152	182	213	244	274	305	335
2	2	33	61	92	122	153	183	214	245	275	306	336
3	3	34	62	93	123	154	184	215	246	276	307	337
4	4	35	63	94	124	155	185	216	247	277	308	338
5	5	36	64	95	125	156	186	217	248	278	309	339
6	6	37	65	96	126	157	187	218	249	279	310	340
7	7	38	66	97	127	158	188	219	250	280	311	341
8	8	39	67	98	128	159	189	220	251	281	312	342
9	9	40	68	99	129	160	190	221	252	282	313	343
10	10	41	69	100	130	161	191	222	253	283	314	344
11	11	42	70	101	131	162	192	223	254	284	315	345
12	12	43	71	102	132	163	193	224	255	285	316	346
13	13	44	72	103	133	164	194	225	256	286	317	347
14	14	45	73	104	134	165	195	226	257	287	318	348
15	15	46	74	105	135	166	196	227	258	288	319	349
16	16	47	75	106	136	167	197	228	259	289	320	350
17	17	48	76	107	137	168	198	229	260	290	321	351
18	18	49	77	108	138	169	199	230	261	291	322	352
19	19	50	78	109	139	170	200	231	262	292	323	353
20	20	51	79	110	140	171	201	232	263	293	324	354
21	21	52	80	111	141	172	202	233	264	294	325	355
22	22	53	81	112	142	173	203	234	265	295	326	356
23	23	54	82	113	143	174	204	235	266	296	327	357
24	24	55	83	114	144	175	205	236	267	297	328	358
25	25	56	84	115	145	176	206	237	268	298	329	359
26	26	57	85	116	146	177	207	238	269	299	330	360
27	27	58	86	117	147	178	208	239	270	300	331	361
28	28	59	87	118	148	179	209	240	271	301	332	362
29	29		88	119	149	180	210	241	272	302	333	363
30	30		89	120	150	181	211	242	273	303	334	364
31	31		90		151		212	243		304		365

FUN FACTS

- developed by Joseph Justus Scaliger in 1583
- named by Joseph in honour of his father Julius Caesar Scaliger
- Day 1 was chosen because the Julian Calendar, the Lunar Calendar and the Roman Tax Calendar all coincided. This happens every 7,980 years.

Modified Julian Dates

- **MJD** = ***Modified Julian Date***

  JD – 2400000.5 (integer at midnight rather than midday)

- **HJD** = ***Heliocentric Julian Date***

  JD of event as measured from the centre of the Sun (corrects for light-travel +/- 8 mins).

- **BJD** = ***Barycentric Julian Date***

  JD of event measured from the barycentre of solar system (another +/- 2 secs relative to HJD)

Universal time (UT1) *(previously Greenwich Mean Time)*

- This is Solar time based on the (variable) spin of the Earth
- Always 86400s/day, but day (and hence sec) has variable length

International Atomic Time (TAI)

- SI second defined by frequency of hyperfine transition of cesium133
- Measured and counted with international network of atomic clocks

Co-ordinated Universal Time (UTC)

- Most times in the literature (JDs, HJDs) are derived from ***UTC***, an atomic time synchronised since 1972 to UT1 by the addition of ***leap seconds***.
- Our civil time (in winter)
- UTC is not suitable for precision times (better than a few seconds), especially over long timescales.

Happy Observing!

The assignment for this session includes a few examples of planning and taking observations.

If you are taking this module for credit, please tackle these and e-mail the answers (thomas.g.wilson@warwick.ac.uk)

The assignment can be downloaded from: https://warwick.ac.uk/fac/sci/physics/mpags/modules/astro/at/observational_astronomy_homework.pdf