VII. Time and Coordinates [v1.3.1]

A. Overview

- Time and position are two critical components to astronomical observation.
  - ◇ Need to time the arrival of signals to study phenomena
  - ◇ Also, just to calibrate the data (e.g. location of Earth around Sun)
- They are two quantities that are, in principle, much easier to measure than all others!
- Lastly, they provide the space-time reference frame for all astronomical investigation
- References
  - ◇ Léna, "Observational Astrophysics"

B. Time

- Definition of 1 second
  - ◇ Historic: 1/24/60/60th of 1 day
    - ▲ We all appreciate that the duration of daylight changes throughout the year
    - ▲ Need a more stable definition than sunrise to sunrise
    - ▲ Although the concept of a day is still of great value to Earthlings
  - ◇ How about the period of Earth's rotation?
    - ▲ That varies too!
    - ▲ Tidal forces from Earth/moon system
  - ◇ SI definition (Physics): "the duration of 9,192,631,770 periods of the radiation corresponding to the transition between the two hyperfine levels of the ground state of the caesium 133 atom"
- International Atomic Time (TAI)
  - ◇ Weighted average of 400 atomic clocks in 50 laboratories world-wide
  - ◇ Time began on January 1, 1972
  - ◇ Proper time on Earth (in our 'geoid')
- Universal Time (UT)
  - ◇ Time on Earth that relates its rotation to the position of distant astronomical sources (usually quasars)
  - ◇ UT1: Defined (conceptually) as the mean solar time at 0° longitude.
    - ▲ Where a day begins with the Sun at 180° longitude
    - ▲ In practice, it is the measured rotation relative to the International Celestial Reference Frame (ICRF)
  - ◇ One measures the Earth's Rotation Angle (ERA) relative to the ICRF
    - ▲ UT1 is then defined by the relation:

$$\mathrm{ERA} = 2\pi(0.7790572732640 + 1.00273781191135448 T_u) \text{ radians} \quad (1)$$

$$\text{with } T_u = (\text{Julian UT1 date} - 2451545.0) \quad (2)$$

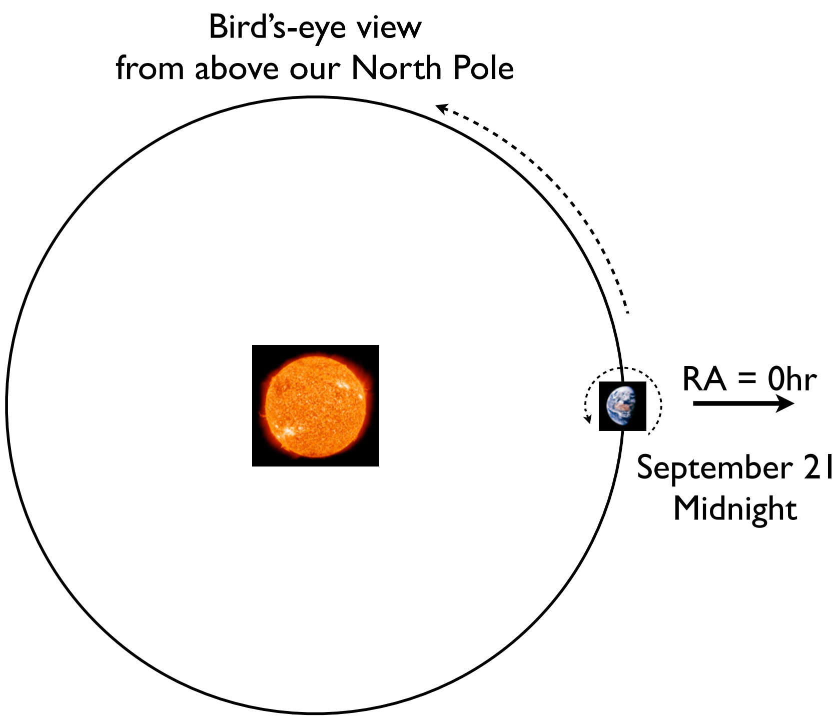
  - Because the Earth's rotation is slowing, UT1 is adjusted regularly and the proper length of a day increases!
- Julian date
  - The interval of time in days and fractions of a day since January 1, 4713 BC Greenwich noon.
  - See: http://curious.astro.cornell.edu/question.php?number=88
    - At 7pm PT on April 9, 2018, the JD=2458218.583333
  - Reduced Julian Date: RJD = JD - 2400000
  - Modified Julian Date: MJD = JD - 2400000.5
- Coordinated Universal Time (UTC)
  - Time system tied to TAI
    - But offset by an integer number of 'leap' seconds
    - Currently +37s
  - Adjusted regularly to be within 1s of UT1
  - This is the fundamental clock of astronomical observation
- Measuring time in astronomical observations
  - Historically, this was a major source of error
  - In modern times, we clock our instruments and telescopes via internet coordination (e.g. Coordinated Universal Time or UTC)
  - For some experiments (e.g. radio observations), one requires and achieves even higher precision
  - http://aa.usno.navy.mil/faq/docs/UT.php
- Tools for Python (Astronomy)
  - This package is rather comprehensive: `astropy.time`
  - See the Notebook for some simple examples

C. Astronomical Coordinates

- Celestial sphere
  - A hypothetical sphere, centered on the Earth, which encloses all objects observed by astronomers.
  - The positions of most objects are given with respect to this coordinate system.
  - Because the Earth's axis moves, the coordinates of otherwise stationary objects *change in time.*
- International Celestial Reference Frame (ICRF)
  - Coordinated reference frame established by the IAU
  - Defined by the highly precise positions of several hundred, very distant (i.e. stationary) sources on the sky (not Earth)

  - ▲ Measured by radio interferometry
  - ▲ Primarily quasars
- ◇ Linked to the FK5 J2000.0 optical system

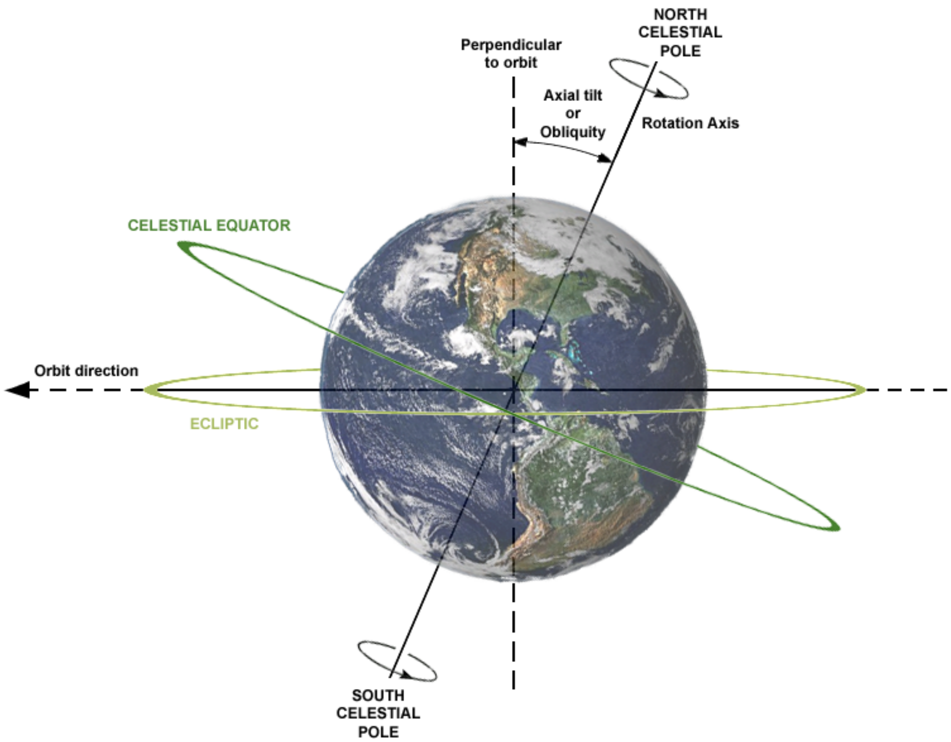
- Declination (DEC or δ)
  - ◇ The angular distance of an object, north or south from the Earth's equator
  - ◇ Measured in degrees, ranging from $-90°$ (celestial south pole) to $+90°$ (celestial north pole)



- Right Ascension (RA or α)
  - ◇ Angular distance from the meridian that passes through the vernal equinox and the poles (see figure)
  - ◇ Measured in the same direction as our motion about the Sun (East)
  - ◇ Most commonly reported in units of time
    - ▲ But angles are measured in degrees not seconds!
    - ▲ And, we measure angles on the sky
  - ◇ Converting to angular units: At DEC $= 0°$
    - ▲ 1 hour $= 15°$
    - ▲ 1 minute $= 15'$
    - ▲ 1 second $= 15''$
  - ◇ Converting to angular units: At DEC $\approx 90°$
    - ▲ 1 hour = ??
  - ◇ Converting to angular units: Off the equator (DEC $= \delta$)

    - ▲ 1 second = $15'' * \cos(\delta)$
    - ▲ e.g., at $\delta = 45°$, 1s of RA is $10.6''$
    - ▲ This conversion is only accurate for small angles

- Examples
  - ◇ M31: RA=00:42:44.330 DEC=+41:16:07.50 (J2000)
  - ◇ LMC: RA=05:23:34.6 DEC=−69:45:22 (J2000)
  - ◇ 3C273: RA=12:29:06.69512 DEC=+02:03:08.6628



- Epoch
  - ◇ Precession of the Earth changes its axis in time relative to stationary objects
    - ▲ Precession constant: $\theta = 50.40''\,\mathrm{yr}^{-1}$
    - ▲ Obliquity of the ecliptic: $\epsilon = 23°27'8''$
  - ◇ Precessing coordinates
    - ▲ For an otherwise fixed object (e.g. a distant quasar), the precessed coordinates may be derived from the measured coordinates at a previous epoch E
    - ▲ Depends on T, the years since E

$$\delta_T = \delta_E + (\theta \sin\epsilon \cos\alpha_E)T \tag{3}$$
$$\alpha_T = \alpha_E + [\theta(\cos\epsilon + \sin\epsilon \sin\alpha_E \tan\delta_E)]T \tag{4}$$

  - ◇ Standard Epochs for object coordinates: 1950, 2000

- Local Sidereal Time (LST)

- ◇ Sidereal day: Time for one rotation of the Earth with respect to distant objects that we do not orbit
  - ▲ Earth's rotation axis is (nearly) aligned with its orbital axis
  - ▲ Therefore, the sidereal day is shorter than the full rotational period
    - ○ Approximately 4 minutes
    - ○ 23.93447 hours
- ◇ Sidereal time: the hour angle of the vernal equinox at that locality
  - ▲ It is defined, therefore, by one's location
  - ▲ And is usually referred to as Local Sidereal Time (LST)
  - ▲ Given the definition, it is very useful for astronomical observations (i.e. it tells you what is up in the sky!)
- ◇ What is your LST now?

- Ephemeris
  - ◇ Table, generated for a specific locality, that describes what is observable in the sky at a given time.
  - ◇ Typically generated by each observatory
  - ◇ Example for Lick Observatory
    - ▲ http://ucolick.org/calendar/lickcal2009-20/index.html
    - ▲ Here is one for April 2012

LICK OBSERVATORY CALENDAR FOR 2012 -ASTRONOMICAL
(computed for altitude 1283.0 m)

DATE(PST) 2012	SUN SET	TWILIGHT ENDS		MOON RISE	MOON SET	DAWN BEGINS		SUN RISE	ASTRONOMICAL(18 deg) SIDEREAL TIMES			TWILIGHT/DAWN NIGHT (18 deg)			MOON(midnight)		
		12	18			18	12		TWI 18	MID	DAWN 18	LENGTH h	DARK h	%	RA h m	DEC d m	Zenith Dist deg
SUN APR 01	18 36	19 27	19 59		03 07	04 22	04 53	05 44	08 36	12 38	17 00	8.4	1.3	14	0853	1158	56
MON APR 02	18 37	19 28	20 00		03 42	04 20	04 52	05 42	08 41	12 42	17 02	8.3	0.6	7	0946	0724	50
TUE APR 03	18 38	19 29	20 01		04 16	04 18	04 50	05 41	08 46	12 46	17 04	8.3	0.0	0	1040	0216	45
WED APR 04	18 39	19 30	20 02	16 26	04 50	04 16	04 49	05 40	08 51	12 50	17 06	8.2	0.0	0	1134	-0312	44
THU APR 05	18 40	19 31	20 03	17 38	05 27	04 15	04 47	05 38	08 56	12 53	17 09	8.2	0.0	0	1231	-0839	46
FRI APR 06	18 41	19 32	20 04	18 50	06 08	04 13	04 45	05 37	09 01	12 57	17 11	8.1	0.0	0	1330	-1341	52
SAT APR 07	18 41	19 33	20 05	20 04	06 53	04 11	04 44	05 35	09 06	13 01	17 13	8.1	0.0	0	1431	-1752	59
SUN APR 08	18 42	19 34	20 06	21 17	07 45	04 10	04 42	05 34	09 11	13 05	17 16	8.1	1.2	14	1534	-2050	68
MON APR 09	18 43	19 35	20 07	22 25	08 42	04 08	04 41	05 32	09 16	13 09	17 18	8.0	2.3	28	1637	-2215	77
TUE APR 10	18 44	19 36	20 09	23 26		04 06	04 39	05 31	09 22	13 13	17 20	8.0	3.3	41	1739	-2210	87
WED APR 11	18 45	19 37	20 10	00 19		04 05	04 38	05 29	09 26	13 17	17 23	7.9	4.2	52	1840	-2056	>90
THU APR 12	18 46	19 38	20 11	01 05		04 03	04 36	05 28	09 31	13 21	17 25	7.9	4.9	62	1937	-1825	>90
FRI APR 13	18 47	19 39	20 12	01 44		04 01	04 35	05 27	09 36	13 25	17 27	7.8	5.5	70	2030	-1502	>90
SAT APR 14	18 48	19 40	20 13	02 18		04 00	04 33	05 25	09 41	13 29	17 30	7.8	6.1	78	2120	-1104	>90
SUN APR 15	18 49	19 41	20 15	02 49		03 58	04 31	05 24	09 47	13 33	17 32	7.7	6.6	85	2208	-0644	>90
MON APR 16	18 50	19 42	20 16	03 18		03 56	04 30	05 22	09 52	13 37	17 33	7.7	7.0	91	2254	-0214	>90
TUE APR 17	18 51	19 43	20 17	03 46		03 55	04 28	05 21	09 57	13 41	17 36	7.6	7.5	98	2339	0215	>90
WED APR 18	18 51	19 44	20 18	04 14	16 50	03 53	04 27	05 20	10 02	13 45	17 38	7.6	7.6	100	0024	0634	>90
THU APR 19	18 52	19 45	20 19	04 44	17 47	03 51	04 25	05 18	10 07	13 49	17 40	7.5	7.5	100	0109	1034	>90
FRI APR 20	18 53	19 46	20 21	05 16	18 43	03 50	04 24	05 17	10 13	13 53	17 43	7.5	7.5	100	0155	1406	>90
SAT APR 21	18 54	19 47	20 22	05 51	19 40	03 48	04 22	05 16	10 18	13 57	17 45	7.4	7.4	100	0242	1702	>90
SUN APR 22	18 55	19 48	20 23	06 30	20 35	03 46	04 21	05 14	10 23	14 00	17 47	7.4	7.2	97	0331	1913	>90
MON APR 23	18 56	19 50	20 24	07 14	21 29	03 45	04 20	05 13	10 28	14 04	17 50	7.4	6.3	85	0420	2035	>90
TUE APR 24	18 57	19 51	20 26	08 03	22 19	03 43	04 18	05 12	10 34	14 08	17 52	7.3	5.4	74	0511	2101	>90
WED APR 25	18 58	19 52	20 27	08 56	23 06	03 42	04 17	05 11	10 39	14 12	17 55	7.2	4.6	63	0602	2028	>90
THU APR 26	18 59	19 53	20 28		23 49	03 40	04 15	05 09	10 44	14 16	17 57	7.2	3.8	53	0653	1856	>90
FRI APR 27	19 00	19 54	20 29		00 28	03 38	04 14	05 08	10 49	14 20	17 59	7.1	3.2	44	0745	1618	87
SAT APR 28	19 01	19 55	20 31		01 04	03 37	04 12	05 07	10 55	14 24	18 02	7.1	2.6	35	0835	1302	80
SUN APR 29	19 02	19 56	20 32		01 38	03 35	04 11	05 06	11 00	14 28	18 04	7.1	1.9	27	0926	0855	73
MON APR 30	19 02	19 57	20 33		02 11	03 34	04 10	05 05	11 04	14 32	18 07	7.0	1.4	19	1017	0411	67

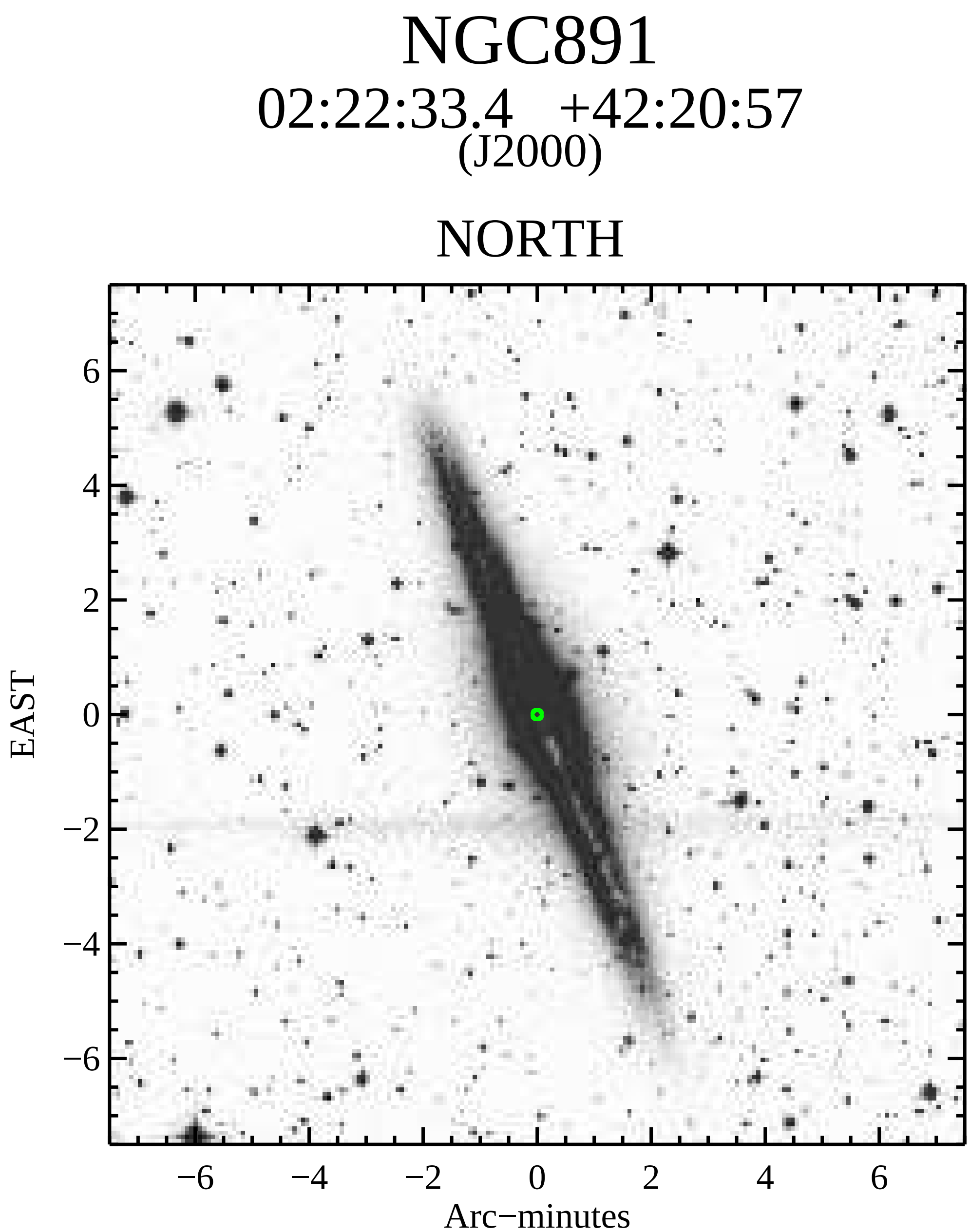
ONE LINE REFERS TO EVENING DATE	FULL MOON	Apr 06	19:18 UT
AND FOLLOWING MORNING.	LAST QUARTER	Apr 13	10:50 UT
All dates and times are zone PST	NEW MOON	Apr 21	07:17 UT
in upper table (except sid time).	FIRST QUARTER	Apr 29	09:59 UT

- Tools for Python (Astronomy)
  - ◇ This package is excellent: `astropy.coordinates`
  - ◇ See the Notebook for some simple examples

D. Astrometry

E. Finder Charts

- An image showing the field of interest for a given observation
  - ◇ Ideally generated at or near the wavelengths of interest
  - ◇ Ideally generated with a size at or exceeding the field of interest
- Sources of 'all-sky' data
  - ◇ Palomar Digital Sky Survey (DSS)
  - ◇ Sloan Digital Sky Survey (SDSS)
  - ◇ Two Micron All Sky Survey (2MASS)
- Generating a finder chart
  - (a) Grab an image of your field from a source
  - (b) Make it pretty
  - (c) Add the coordinates (use the right Epoch!)
  - (d) Print
- SDSS Finder: http://cas.sdss.org/dr7/en/tools/chart/chart.asp


NGC891
02:22:33.4 +42:20:57
(J2000)
NORTH
EAST
Arc−minutes
6
4
2
0
−2
−4
−6
−6
−4
−2
0
2
4
6