PROCEEDINGS OF SCIENCE

Scales and orders of magnitude in Astronomy

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As an introduction to the forthcoming units, I will review in this one the typical scales used in Astronomy for the most important physical magnitudes, such as size and distance, mass, time, speed, and energy.

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1. Introduction: Astronomical units

Astronomy is the science that studies the bodies, processes and phenomena occurring outside the Earth's atmosphere. Yet it also deals with substances that found in the Earth are of extraterrestrial origin. Because of its subjects of study, Astronomy is a very broad science, where observations have larger impact than laboratory studies. Astronomy deals with systems extremely large and at the same time very far away from us. These systems, may consist in much more smaller components, sometimes even of microscopic size. In addition, in Astronomy we study both very energetic processes as well as emissions arising from systems nearly at the absolute zero of temperature. These processes can be very fast, lasting for just a few seconds, or be very slow lasting thousands of million years.

All these characteristics make that the quantities measured in Astronomy may have a very large range of values, from very small figures to very large ones. The handling of very large or very small figures is not very practical, this is why in Astronomy we use a broad variety of units for the same physical magnitude. These units are typically used in those contexts for which they may result better suited. This general tendency in Astronomy difficults up to some point the comprehension of the relevant scales and orders of magnitude for those who are not very familiar with the field. Since this school is not intended just for radio astronomers, even not just for astronomers, as an introduction to the forthcoming units, I am going to review the typical scales used in Astronomy for the most important physical magnitudes: size and distance, mass, time, speed, and energy.

2. Sizes and size units in Astronomy

- Typical size nucleons — femtometers (fm = 10^{-15} m)
- Typical size of atoms and small molecules — Ånströngs (Å= 10^{-10} m)
- Circumstellar and interstellar dust grains — microns (μm = 10^{-6} m)
- Micro-meteorites — millimeters (mm = 10^{-3} m)
- Meteorites and comets — meters — kilometers (m, km = 10^{3} m)
- Planets, satellites and large asteroids — thousands of kilometers
  - The Earth — $1.3\,10^{4}$ km
  - Mercury — $4.9\,10^{3}$ km
  - Jupiter — $1.4\,10^{5}$ km
  - The Moon — $3.5\,10^{3}$ km
  - Io — $3.6\,10^{3}$ km
  - Titan — $5.1\,10^{3}$ km;
  - Ceres — $9.3\,10^{2}$ km
- Stars — Solar radius ($R_\odot$= $7\,10^{5}$ km = $4.6\,10^{-3}$ AU)

- Dwarf stars — 0.01 — 0.1 $R_\odot$
- Red giants and supergiants — 100 — 1000 $R_\odot$

- Planetary systems — Astronomical Units (AU = $1.5\,10^8$ km = $4.8\,10^{-6}$ pc)
  - Orbit of Neptune — 60 AU
  - Kuiper belt — 2000 AU
- Molecular clouds — parsecs (pc = $3\,10^{16}$ m = $2\,10^5$ AU)
  - Dark clouds — 1 — 20 pc
  - Giant clouds — 50 — 100 pc
- Galaxies — kiloparsecs (kpc = 10^3 pc = $3\,10^{19}$ m)
  - Spiral galaxies — 5 — 250 kpc
    The Milky Way — 50 kpc
  - Elliptical galaxies — 1 — 200 kpc
  - Irregular galaxies — 1 — 10 kpc
- Active Galactic Nuclei (AGNs)
  - Giant radio-emitting lobes in 3C273 — 5.000 kpc
  - Central engine of the AGN (M 87) — $\lesssim 0.08$ pc $\sim 1.6\,10^4$ AU
- Galaxy clusters — megaparsecs (Mpc = 10^{+6} pc = $3\,10^{22}$ m)
  - Cluster — several Mpc
  - Super-clusters and voids — several tens of Mpc

3. Distances in Astronomy

- Planetary Systems — Astronomical Units (AU = $1.5\,10^8$ km = $4.8\,10^{-6}$ pc)
  - Radius of the orbit of Mercury — 0.39 AU
  - Radius of the orbit of the Earth — 1 AU
  - Radius of the orbit of Neptune — 30 AU
  - Radius of the orbit of the Moon — 0.0025 AU ($3.8\,10^5$ km)
  - Radius of the orbit of the innermost satellite of Jupiter — 0.0008 AU ($1.3\,10^5$ km)
  - Radius of the orbit of the outermost satellite of Jupiter — 0.2 AU ($3.5\,10^7$ km)
- Distances between stars in our Galaxy — several pc — several kpc
  - Distance from the Sun to Proxima Centauri — 1.3 pc
  - Number of stars closer than 5 pc to our Sun — ~ 40

- Distance from the Sun to Taurus (dark molecular cloud) 140 pc
- Distance from the Sun to Orion (giant molecular cloud complex) 500 pc
- Distance from the Sun to the center of our Galaxy 8500 pc (8.5 kpc)

• Distance to other Galaxies in the Local Group tens of kpc — Mpc

- Distance to the Magellanic Clouds 50 — 60 kpc
- Distance to the Andromeda Galaxy (M 31) 750 kpc
- Distance to Leo A (the farthest one) 2300 kpc

• Distances to other nearby galaxies up to 20 — 30 Mpc

- Distance to M 51 11 Mpc

• Distances to distant galaxies hundreds to thousands of Mpc

We can also use red-shift units (z). Due to the Doppler effect, the wavelength λ of the electromagnetic waves (EMWs) radiated by an emitter which is moving away from us at a speed v, will change according to the law:

$$\lambda = \lambda_0(1+z) \quad ; \quad z = \frac{\lambda - \lambda_0}{\lambda_0} = \sqrt{\frac{c+v}{c-v}} - 1$$

where λ is the wavelength observed by us, λ_0 is the wavelength in the reference frame of the emitter (at rest) and c is the speed of light in vacuum ($\sim 299\,792.458\,\mathrm{km\,s^{-1}}$).

According to the Hubble law, the distance to the distant galaxies is proportional to the speed at which the galaxy is receding from us, as consequence of the Big Bang:

$$D = \frac{v}{H_0} \quad ; \quad H_0 \sim 75\,\mathrm{km\,s^{-1}\,Mpc^{-1}} \quad ; \quad v = c\,\frac{(1+z)^2-1}{(1+z)^2+1}$$

where D is the distance in Mpc. (We are assuming that there has not been acceleration nor deceleration in the Universe since the Big Bang, i.e. $q_0 = 0$ and $\Lambda_c = 0$, which today we know is not true). Therefore, knowing the red-shift we can estimate the distance to a very far away object. Using the parameters above we obtain the following conversion table:

- z = 0.1 ⇒ D = 380 Mpc
- z = 0.5 ⇒ D = 1500 Mpc
- z = 1.0 ⇒ D = 2400 Mpc
- Typical distance to quasars z = 3.0 ⇒ D = 3500 Mpc
- Dist. to the farthest radio-quasar z = 6.2 ⇒ D = 3850 Mpc
- Dist. to the most distant galaxy (with well known red-shift) z = 6.96 ⇒ D = 3900 Mpc

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4. Masses and mass units in Astronomy

- Planets — mass of Jupiter (M_{Jup}= $1.9\,10^{27}$ kg $\approx 0.001\,M_{\odot}$)
  - The Earth — $3.2\,10^{-3}\,M_{Jup}$
  - Planets — $< 0.013\,M_{\odot}$ ($< 13\,M_{Jup}$)
- Stars — solar masses ($M_{\odot}$= $2.0\,10^{30}$ kg $\approx 1000\,M_{Jup}$)
  - The Sun — $1\,M_{\odot}$
  - Normal stars — 0.08 — $100\,M_{\odot}$
  - Brown dwarfs — 0.013 — $0.08\,M_{\odot}$
  - Stellar size black holes — several $M_{\odot}$
- Molecular clouds
  - Taurus (dark molecular cloud) — $10^4\,M_{\odot}$
  - Orion (giant molecular cloud) — $5\,10^5\,M_{\odot}$
- Nuclei of galaxies
  - Super-massive black hole in Sgr A* (Milky Way) — $2.6\,10^6\,M_{\odot}$
  - Super-massive black hole in a typical AGN — 10^7 — $10^9\,M_{\odot}$
- Galaxies
  - Spiral galaxies — 10^9 — $4\,10^{11}\,M_{\odot}$
  - Elliptical galaxies — 10^5 — $10^{13}\,M_{\odot}$
  - Irregular galaxies — 10^8 — $3\,10^{10}\,M_{\odot}$

5. Energies and power units in Astronomy

Rather than about Energy, in Astronomy we usually talk about Luminosity, which is the energy emitted by a certain source per unit of time, i.e. it is the power emitted by the object (not only by means of EMWs but by all means). Luminosities are always measured in units of the luminosity of the Sun, i.e. solar luminosities, $L_{\odot} = 3.9\,10^{26}$ W ($3.9\,10^{33}$ erg s^{-1}).

- Stars
  - Low mass stars and white dwarfs — 10^{-4} — $10^{-2}\,L_{\odot}$
  - Our Sun — $1\,L_{\odot}$
  - Giant, super-giant, and hyper-giant stars — 10^4 — $10^6\,L_{\odot}$
  - Supernova explosions — 10^8 — $10^{10}\,L_{\odot}$
- Galaxies

  - Normal spiral galaxies 10^8 — $2\,10^{10}$ $L_\odot$
  - Normal elliptical galaxies $3\,10^5$ — 10^{11} $L_\odot$
  - Irregular galaxies 10^7 — 10^9 $L_\odot$

- Active galactic nuclei (AGNs) 10^8 — 10^{14} $L_\odot$

6. Time scales in Astronomy

Usually, time in Astronomy is measured as in normal life in seconds (s), minutes (m), hours (h), days (d) and years (yr). The most common unit is the year, since in general astronomical processes evolve very slowly in comparison with human standards. Nevertheless, for very fast events, such as explosive phenomena, variability, etc., seconds and days are the preferred units.

- Age of the Universe after WMAP results 13.7 Gyr ($1.37\,10^{10}$ yr = $4.1\,10^{17}$ s)
- Age of the Universe at the end of the primordial nucleo-synthesis 1000 s
- Age of the Universe at the Recombination Epoch 300.000 yr
- Age of the Sun and Solar System 4.6 Gyr
- Stars: duration of their lives while in the main sequence
  - Star with 0.5 $M_\odot$ 200 Gyr
  - Star with 1.0 $M_\odot$ 10 Gyr
  - Star with 3.0 $M_\odot$ 0.5 Gyr
  - Star with 25 $M_\odot$ 0.005 Gyr
- Stellar variability seconds — years
- AGNs
  - Duration of the activity period of AGNs $\sim$ several Gyr
  - Variability timescale in AGN several hours — several tens of yr (10^4 — 10^9 s)

Sometimes, from the variability timescales we can roughly estimate the size of the emitting region along the line of sight. We just need to multiply the typical time scale of the fluctuations of the by the speed of light, to obtain the typical size of the emitting region.

7. Speeds in Astronomy

Speeds are normally measured in km s^{-1}, except when they are close to the speed of the light *c*, when they are usually given in units of fractions of *c*.

- Maximum possible speed, *c* (just for massless particles) 299 792.458 km s^{-1}

- Receding speed of the most distant galaxy (z = 6.96) 0.97 c (290.500 km s^{-1})

- Orbital velocities

$$\frac{mv_{\mathrm{orb}}^2}{r} = G\,\frac{Mm}{r^2} \quad\Rightarrow\quad v_{\mathrm{orb}} = \sqrt{\frac{MG}{r}}$$

where G is the Gravitational constant (6.673 (10) 10^{-11} m^3 kg^{-1} s^{-2}) and M is the mass of the attracting body.

  - Orbital speed of the Moon (around the Earth) 1 km s^{-1}
  - Orbital speed of the Earth (around the Sun) 30 km s^{-1}
  - Orbital speed of Neptune (around the Sun) 5.5 km s^{-1}
  - Orbital speed of the Sun (around the center of the Galaxy) 220 km s^{-1}
  - Orbital speed of the S1 star (Sgr A*) 1 400 km s^{-1}
  - Orbital speed of the central regions of M 84 700 km s^{-1}
  - Orbital speed of the H_2O masers in the Seyfert galaxy NGC 4258 1 000 km s^{-1}

- Ejection speeds. They are usually similar to the corresponding escape velocities v_{esc}

$$\frac{1}{2}mv_{\mathrm{esc}}^2 = G\,\frac{Mm}{r} \quad\Rightarrow\quad v_{\mathrm{esc}} = \sqrt{\frac{2MG}{r}}$$

  - Escape velocity of the Earth 12.2 km s^{-1}
  - Escape velocity of the Sun 617.7 km s^{-1}
  - Expansion velocity in circumstellar envelopes of AGB stars 10 — 20 km s^{-1}
  - Speed of the bipolar jets ejected by young/old stars up to several 100 km s^{-1}
  - Expansion speed of supernova remnants $\sim$ 1000 km s^{-1}
  - Speed of the bipolar jets ejected by AGNs some fraction of c

- Velocities due to thermal agitation in a gas

$$\frac{1}{2}mv^2 = \frac{1}{2}kT \quad\Rightarrow\quad v = \sqrt{\frac{kT}{m}} \quad\equiv\quad v\,(\mathrm{km\,s^{-1}}) = 0.09\,\sqrt{\frac{T\,(\mathrm{K})}{m\,(\mathrm{aum})}}$$

where T is the temperature of the gas, k the Boltzman constant, and m the mass of the gas particles.

- Velocities due to turbulent motions some km s^{-1}

- Sound speed in a gas v_s

$$v_\mathrm{s} = \sqrt{\frac{\gamma k T}{m}}$$

where m is the average mass per gas particle. γ takes 5/3 or 1 depending on whether we talk about adiabatic sound speed or isothermal sound speed, respectively. Assuming an ideal gas consisting in molecular Hydrogen and atomic Helium in a 3 to 1 relationship, we have:

$$m = 2.25\ (\mathrm{uma}) \quad ; \quad v_\mathrm{s}\,(\mathrm{km\,s^{-1}}) = 0.07\ \sqrt{\gamma T\,(\mathrm{K})}$$

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