Cosmology

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Apart from electromagnetic radiation also **elementary particles** arrive on Earth from space.

For the purposes of astronomy and particularly, extragalactic astronomy, their use is limited, because:

- Electrically charged particles are deflected by electromagnetic fields and material between the source and the observer on Earth, making it imposible to determine the original source of emission.
- By far the most elementary particles arriving on Earth are emitted by the Sun.
- In principle, neutrinos interact so weakly on their path from emission far away in space to their arrival on Earth that they might be tracked to their source of emission. But the weak interaction of neutrinos with any form of matter makes it very hard to detect them – to the effect that there is no angular and extremely limited spectral resolution of neutrinos detected on Earth. Again, most of the neutrinos arriving on Earth originate from the Sun.

Nevertheless, neutrino astronomy has some interesting aspects and intances —

- Around 3 hours prior to the optical observation of the supernova SN1987A, an increased neutrino detection was observed in the Kamiokande 2 and IMB detectors. That is believed to be caused by the supernova forming process where neutrinos can escape the very dense collapsing shell of a star (which heats up enormously, starting nuclear fusion processes) while electromagnetic radiation is still trapped until the outer shell thermally explodes. [http://adsabs.harvard.edu/full/1989ApJ...340..426L]
- An extremely high energy neutrino was observed in the IceCube detector in Antarctica in 2017. It has been traced back to have had as its source the blazar TXS 0506+056. [https://science.sciencemag.org/content/361/6398/eaat1378.full]
- The theory of big bang nucleosynthesis predicts a thermally distributed, homogeneous and isotropic **cosmic neutrino background** where the temperature depends on the number of neutrino generations. We will derive this result later. Presently, this neutrino background cannot be observed; if it could, it would again very strongly support the "big bang cosmology" picture, and give further insights to our understanding of elementary particle physics.

Apart from electromagnetic radiation and elementary particles, also **gravitational waves** can be detected on Earth.

- The first detection of gravitational waves in 2014 by the LIGO interferometers has recorded the merger of two stellar size black holes. See the web page for a link to the original article. This has also been the first observational evidence for stellar size black holes.
  The LIGO interferometers have since also detected further gravitational wave events, see
  [https://www.ligo.caltech.edu/page/detection-companion-papers]
- Prior to direct detection of gravitational waves, an indirect evidence for their existence was inferred from the Hulse-Taylor pulsar, a binary star system whose revolution time is decreasing and the loss of energy is accounted for by the radiation of gravitational waves.
  [https://en.wikipedia.org/wiki/Hulse%E2%80%93Taylor_binary]
- Gravitational wave astronomy is of great significance for cosmology: It could reach beyond the “surface of last scattering” at recombination, revealing signatures of early inflation, and give insight into the nature of dark matter, and galaxy formation

2.2. Observables

Now we turn to the quantities that one can observe — and some conclusions that can be drawn.

Drawing conclusions usually refers to some theoretical concepts and assumptions. As indicated, we start by making the assumption (later seen to be inappropriate) that the spacetime concept suitable for the description of the Universe is Minkowski space of special relativity. That fixes the space geometry to be Euclidean, and it also makes a basic hypotheses about the propagation of light. Both of these hypotheses are instrumental for distance determination of luminous objects in the sky.

We proceed by fixing some terminology augmented by some explanations.
Note: Some of the terminology may differ from that in the literature (at least in details) even if similar words are used.

The **Universe** is “the whole world” but that is meant mostly in a theoretical sense: It is a spacetime manifold which models the whole world that is, in principle, accessible to large (potentially infinite) families of observers. In contrast, there is

The **visible Universe** which is the part of the Universe that so far, in principle, is/has been accessible to terrestial observers. Often, it is convenient to use the Universe as a theoretical concept instead of the visible Universe since it permits to formulate some idealizations or theoretical concepts, like symmetry assumptions (related to homogeneity and isotropy) more simply and clearly. However, one should keep in mind that this already involves quite some theoretical idealization.

The distinction will be clearer when we look at Minkowski spacetime more concretely. We assume that an inertial system is given in which the Earth (or rather, the Sun) is approximately at rest.

Then Minkowski spacetime is canonically identified with $\mathbb{R}^4 \simeq \mathbb{R} \times \mathbb{R}^3$.
An event in the spacetime is then described by $(t, \boldsymbol{x}) \in \mathbb{R} \times \mathbb{R}^3$;
$t \in \mathbb{R}$ is time-coordinate of the event and
$\boldsymbol{x} = (x^1, x^2, x^3) \in \mathbb{R}^3$ are the space-coordinates of the event w.r.t. the chosen inertial coordinate system.

Then one has:

the **Universe** = $\mathbb{R}^4 \simeq \mathbb{R} \times \mathbb{R}^3$, i.e. the whole spacetime, or all events in the spacetime.

On the other hand, any observer in the spacetime has a worldline. If the observer is at rest with respect to the inertial coordinate system chosen, then the worldline is of the form

$$t \mapsto \gamma_o(t) = (t, \boldsymbol{x}_o) \qquad (t \in \mathbb{R})$$

where the subscript o has been used as a label for the observer. Note also that t is proper time for the observer since the observer is assumed at rest w.r.t. the inertial system.

If the observer looks at the sky exactly at the time t_o, then the events of which the observer can receive light at that instant in time are all contained in the **past lightcone** of the event $\gamma_o(t_o) = (t_o, \boldsymbol{x}_o)$,

$$C^-(t_o, \boldsymbol{x}_o) = \{(t', \boldsymbol{x}') : t' \leq t_o, \;\; c^2(t' - t_o)^2 - |\boldsymbol{x}' - \boldsymbol{x}_o|^2 = 0\}$$

where c is the velocity of light (in empty space) and $|\boldsymbol{y}|$ is the standard Euclidean norm of $\boldsymbol{y} \in \mathbb{R}^3$.

If, more realistically, the observer makes continuous observations for some time interval $\mathrm{I} = [t_1, t_2]$, then the light received by the observer during that time interval must have been emitted from events within the associated union of past lightcones,

$$C^-(\gamma_o(\mathrm{I})) = \bigcup_{t\in\mathrm{I}} C^-(t, \boldsymbol{x}_o)$$

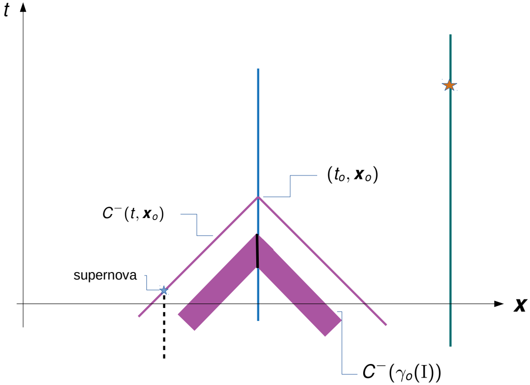


Illustration of the past lightcones. In spacetime diagrams, $c = 1$, so lightrays are 45-degree straight lines. The blue vertical line is the worldline of the Earth. The blue supernova can be observed on Earth at time t_o. The black segment on Earth's worldline corresponds to the time interval I. The orange supernova on the green worldline cannot be observed on Earth at t_o, or before.

If $\mathrm{I} = [-\infty, t_o]$, then $C^-(\gamma_o(\mathrm{I}))$ are all the events from which light signals may have been recorded on Earth — provided continuous observations had taken place over the full history up to the point in time t_o. In our present setting, where the spacetime is Minkowski spacetime, $C^-(\gamma_o([-\infty, t_o]))$ coincides with

$$J^-(t_o, \boldsymbol{x}_o) = \{(t', \boldsymbol{x}') : t' \leq t_0,\ c^2(t' - t_o)^2 \geq |\boldsymbol{x}' - \boldsymbol{x}_0|^2\}\,,$$

the **causal past** of the event $(t_o, \boldsymbol{x}_o)$. It contains all events which can be reached by a causal (lightlike or spacelike curve), past-directed worldline from $(t_0, \boldsymbol{x}_o)$. (We will develop this terminology later more systematically.) In other words, the causal past is the part of spacetime events about which the observer up until $(t_o, \boldsymbol{x}_o)$ could have in principle obtained knowledge by continuously collecting all carriers of information — light signals and material objects.

Therefore, the causal past $J^-(t_o, \boldsymbol{x}_o)$ is the **visible Universe** for an observer at $(t_o, \boldsymbol{x}_o)$. Note that $t_1 \geq t_o \Rightarrow J^-(t_1, \boldsymbol{x}_o) \supset J^-(t_o, \boldsymbol{x}_o)$ so the visible Universe of an observer increases with time. Note also that the concept of “visible Universe” is already a considerable idealization in view of what is theoretically observable, and what is actually being observed.

A **stellar object** is basically anything which can be observed, directly or indirectly, in space, by the current means of observation, and is sufficiently distinctive from the "background" and recognizable for a sufficient amount of time. We use this term quite loosely. Typically, it is intended to mean **luminous stellar object**, emitting electromagnetic radiation, such as:

Stars (including Neutron stars), supernovae, stellar clusters, galaxies, galaxy clusters.

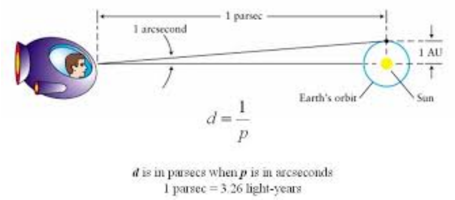
Non-luminous, stable and distinct aggregations of matter would also be regarded as stellar objects, such as:

Planets, non-luminous stars (brown dwarfs), (isolated) black holes (without luminous accretion neighbourhood).

On the other hand, large aggregations of "dust" (interstellar or intergalactic gas clouds composed of Hydrogen or Helium) are not regarded as stellar objects, as similarly aren't large aggregations of dark matter. We call them broadly **matter aggregations**.

Keeping in mind that for the time being, we assume the Minkowski spacetime geometry, with the Euclidean space geometry, and that we also have chosen inertial coordinates in which the terrestial observer is approximately at rest, there are the following **distance scales** which are relevant within our galaxy:

- 1 ℓy = 1 light year = distance travelled by a light light signal (straight line) without interaction in 1 year (= 365.25 $\times$ 86.400 s) $\approx$ 9.461 $\times$ 10^{15} m
- 1 AU = 1 astronomical unit = mean radius of Earth's orbit around the Sun $\approx$ 1.496 $\times$ 10^{11} m
- 1 pc = 1 parsec = parallax of 1 arcsecond. This is the distance from which the (mean) radius of Earth's orbit around the Sun appears under 1 arcsecond.



Note that $1'' = 1$ arcsec = 1 arcminute/60 and 1 arcminute = 1 degree/60 so in radians, 1 arcsecond is the $1/(360 \times 3600)$th part of the unit arc $(2\pi/(360 \times 3600)$ rad).

Note also that the formula given in the illustration shown on the previous slide is only approximate — but suffiently accurate for most purposes; the definition of a parsec is exactly given by

$$1\ \mathrm{pc} = \frac{1\ \mathrm{AU}}{\tan(1'')} \approx 3.086 \times 10^{16}\,\mathrm{m} \approx 3.26\,\ell y$$

The angular resolution of the human eyes is around $30''$ under very good conditions. This means that two similar rectangular buildings that are 1 meter apart can be seen distinct from a distance of 3 km.

The angular resolution of the Hubble space telescope is approximately $0.08''$. This means that the imprint on a coin ($\simeq 0.1$ mm) can be read from a distance of 2 km.

The angular resolution reached in very long baseline interferometry used in radio astronomy is in the range of a few microarcseconds.

Some common length scales:

- 1 kpc (kiloparsec) = 10^3 pc
- 1 Mpc (Megaparsec) = 10^6 pc
- 1 Gpc (Gigaparsec) = 10^9 pc
- Aphelion of the orbit of Pluto = 50 AU $\approx 2.5 \times 10^{-4}$ pc
- distance to Proxima Centauri ≈ 1.29 pc
- distance of Earth to the galactic center ≈ 8 kpc
- diameter of our Milky Way ≈ 30 kpc
- distance to the Andromeda galaxy M31 ≈ 0.8 Mpc
- distance to the next galaxy cluster (Virgo cluster) ≈ 18 Mpc