Astrophysics across the electromagnetic spectrum (and beyond)

Relativistic Astrophysics and Cosmology: Lecture 8

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Monday 23rd October 2023

Pre-lecture question:

Is it coincidence that the atmosphere is transparent in the optical band?

Last time

- Compact objects
- Thermal and degeneracy pressure
- The life cycle of stars

This lecture

- From radio to gamma ray astronomy
- Multimessenger astronomy
- High-energy physical processes

Next lecture

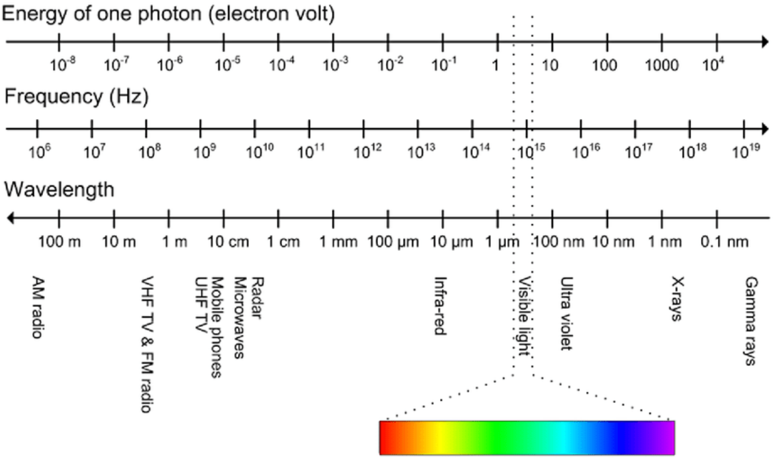
- Accretion disks

The electromagnetic spectrum

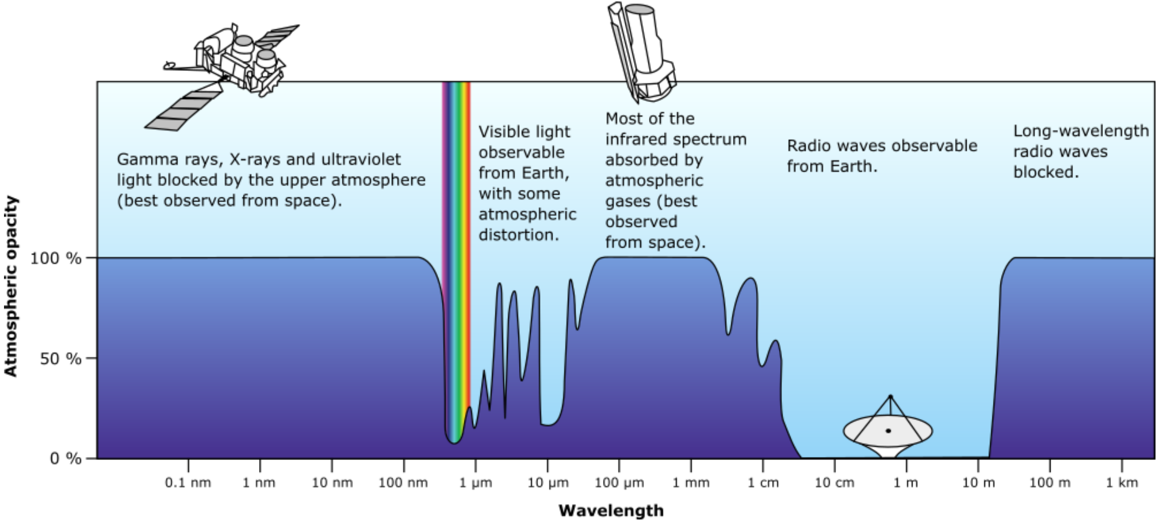
- We generally refer to radiation using any of:
  - photon energy E.
  - frequency ν .
  - wavelength λ.

  which are related by

  $$\boxed{\nu\lambda = c \quad E = h\nu}$$
- Different energies of light correspond to different kinds of astrophysical processes we can observe.
- Excellent resource for seeing this interactively: `https://sky.esa.int/`



The atmosphere

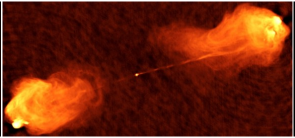


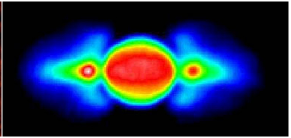
The atmosphere

- The only astronomy we can easily do from the ground is optical, microwave and radio
- Moving telescopes to space gets round this issue, but historically adds an order of magnitude in both cost and time.
- If Elon Musk & Jeff Bezos continue with mega-constellations, everything will have to be done in space (though it will likely be cheaper).
- Experiments in the near future (e.g. DAPPER) will be placed on the moon.
- It seems remarkable that 400-700nm is exactly the window that we see in and that the atmosphere is transparent to – textbook answer: life evolved to fit in this window.
- However this is only partially true – technically the only kind of radiation that biomolecules could interact with is around optical wavelengths (active portion of proteins are of orders of 100s of nanometres).
- Molecules like Rhodopsin and Chlorophyll evolved to fit the gap that was there, but if not life would have no way of coupling to electromagnetism (and would have to e.g. use thermal vents (thermotrophs) or hydrochloric acid (chemotrophs)).

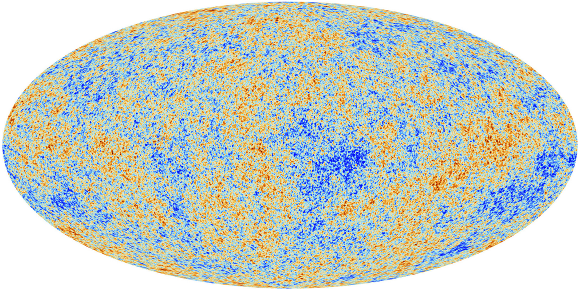
Radio astronomy

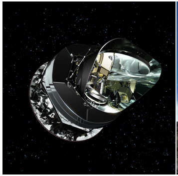
- Two main kinds: Radio telescopes and Interferometers
- Sources: Jupiter, Galactic centre (Saggitarius A*, Event Horizon telescope), Supernova remnants, Neutron stars (Pulsars), Neutral Hydrogen gas clouds, Radio galaxies (M87), Quasars, Fast Radio Bursts.
- Main physical process for generating radio waves is synchrotron radiation, i.e. strong magnetic fields gyrating free electrons.
- Experiments: FAST, HERA, REACH, EHT.
- Future: Square Kilometre Array.

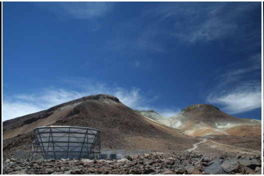


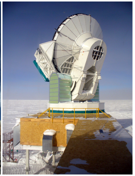


Microwave astronomy



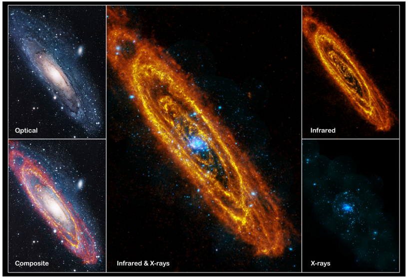


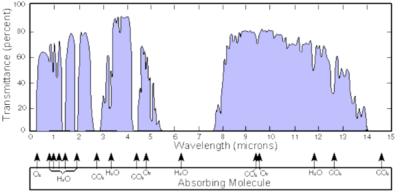




- Sources: our galaxy & the big bang.
- A lot of cross-over here with the radio.
- Some can be done from the ground in high, dry deserts (South pole & Atacama in Chile), but space is essential for large angular scale.
- Physics is usually from much higher wavelengths, but so distant to have redshifted down to the microwave (optical$\rightarrow$microwave $\equiv z_* \approx 1000$).
- Much work at the moment using the CMB as a "back-light" for imaging the dark ages.
- Experiments: COBE, Planck, ACT, SPT.
- Future: Simons Obs, CMBS4, LiteBird.

Infra-red astronomy



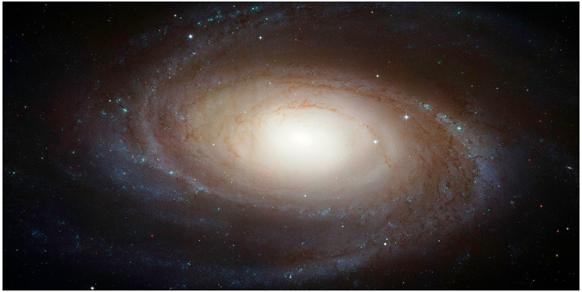


- Due to atmospheric absorption (greenhouse effect) usually in space or airborne, although some windows exist from the ground (particularly in high, dry deserts).
- Additionally complicated by the fact that many things (including the instrument itself) are strong IR emitters.
- Sources: radiative cooling, molecular vibrational and rotational lines.
- Comes in "Near-IR", "Mid-IR" and "Far-IR" varieties.
  - Near-IR: 1000-5000K, Cooler red stars, Red giants, Transparent Dust.
  - Mid-IR: 100-1000K, Planets, comets and asteroids, Dust warmed by starlight, Protoplanetary disks.
  - Far-IR: 10-100K, Emission from cold dust, Central regions of galaxies, Very cold molecular clouds.
- Experiments: Spitzer, WISE, Herschel (COBE & Hubble).

Optical astronomy

- Many physical processes emit in the optical band, although the main reason for emphasis is atmospheric transparency, and that instruments can be repurposed for astronomy (Galileo's telescope, or CCDs).
- Spectroscopy a vital tool for characterising.
- Adaptive optics & Laser guide stars can be used to improve ground based observations .
- Experiments: HST, Gaia, James Webb Space Telescope (JWST).
- Future: Extremely Large Telescope (ELT).

Ultraviolet astronomy

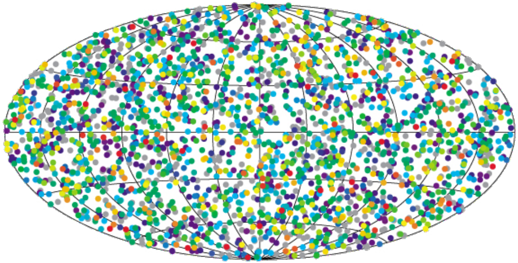


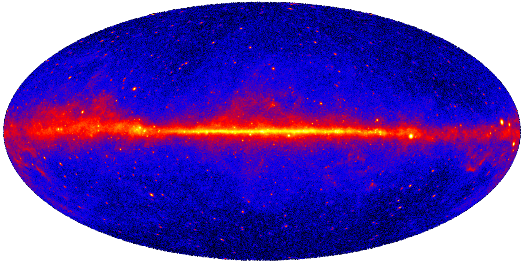
- Ultraviolet line spectroscopy substantially extends the range of optical spectroscopy.
- Important for determining the chemical composition, density and temperature of young stars and the interstellar medium, and is very important for understanding galactic evolution.
- Pictures show the galaxy Messier 81 (M81) in the optical and UV. NB: “Messier” classification comes from a list of 110 objects made in 1774 of “non-comet objects”.
- Experiments: Hubble, FUSE, GALEX.

X-ray astronomy

- Wide variety of sources: clusters, BH, AGN, SNe, Stars, cataclysmic variables, X-ray binaries, Sun (& Moon – reflected) & X-ray background.
- This continuum arises from a wide variety of high-energy processes (Bremsstrahlung, coulomb, black body, synchrotron, inverse Compton, atomic recombination and X-ray transitions).
- X-rays by degree are graded "Hard" / "Soft", hard X-rays: $E > 5 - 10$keV, $\lambda < 0.2\,$nm.
- Experiments: XMM-Newton, INTEGRAL, Swift, Chandra, IXPE.
- Future: Athena (100x).

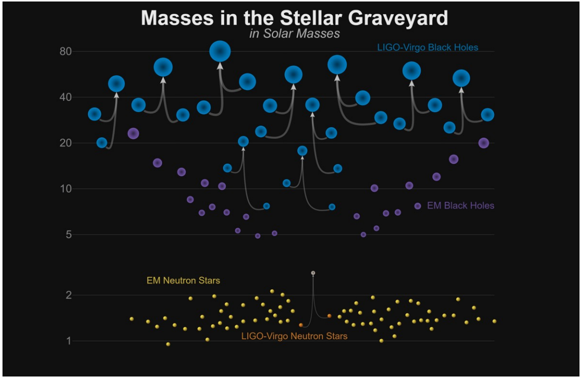
Gamma-ray astronomy

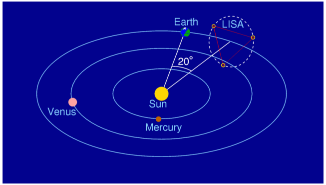




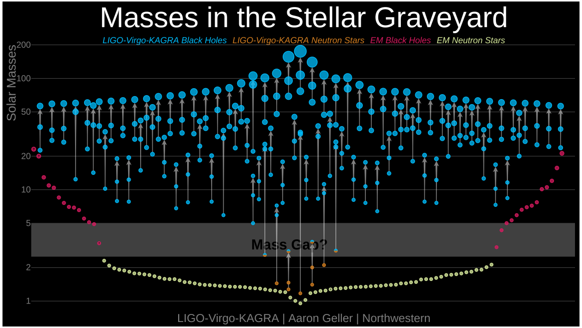
- Same X-rays, a wide variety of mechanisms for generation, but higher energy, and also including decay of radioactive material.
- Observe from space, or showers from ground.
- Sources: Gamma-ray bursts, supernovae, merging NS, hypernovae, pulsars, blazars & magnetars.
- In May 2021, LHAASO detected a shower of a dozen PeVatrons – 1.4 PeV photons (the highest energy photons ever observed).
- Experiments: Fermi, EGRET, INTEGRAL, AGILE, Swift, HESS, VERITAS.
- Future: e-ASTROGAM (100x CGRO).

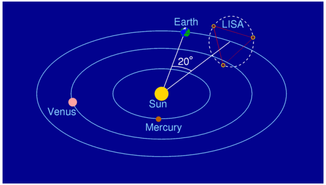
Gravitational wave astronomy





- In 2015 LIGO made the first gravitational wave observation of merging black holes.
- There is a whole spectrum of gravitational waves, with different energy scales and source types associated with them.
- An extremely rapidly advancing field (compare this slide from last year).
- Sources: merging BH-BH, BH-NS, NS-NS, gravitational wave background.
- Experiments: LIGO, Virgo, Kagra.
- Future: LISA (space), Einstein telescope, atomic interferometry?





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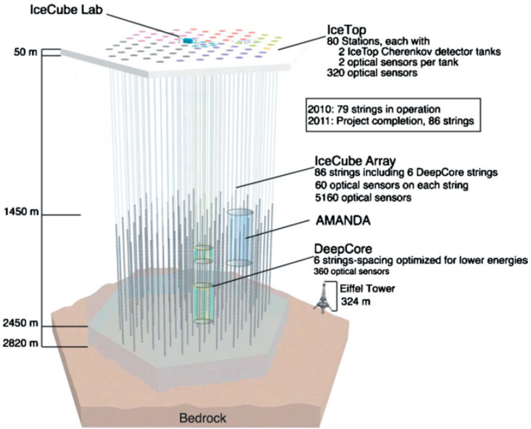
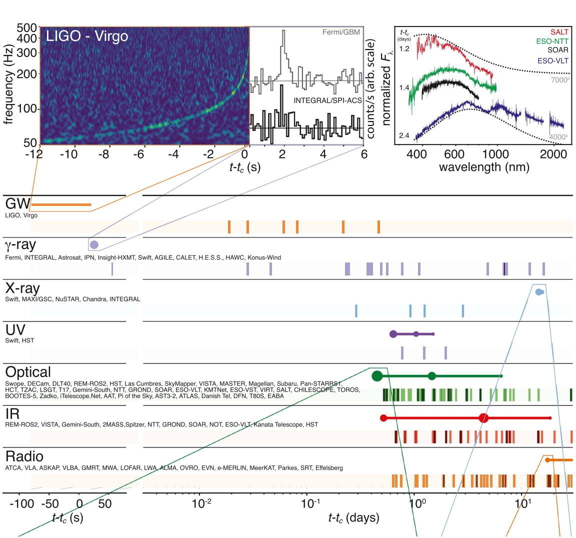
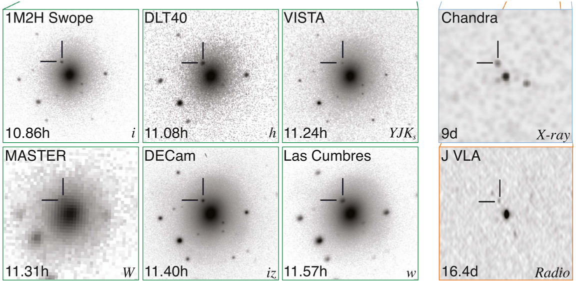
Neutrino astronomy



- Sources: Supernova, high-energy astrophysical events, solar processes.
- Supernova warning system – neutrinos can reach ahead of photons due to intermediate interactions with matter, detection of high-energy astrophysical events, stellar processes.
- In 2018 IceCube announced that they had detected a high-energy neutrino back to a blazar 3.7 bly away.
- Experiments: Super-K, LVD, IceCube, KamLAND, Borexino, Daya Bay, HALO.
- Future: Many! the trick is getting them cheaper and larger.

Multimessenger astronomy





- Can now combine several channels.
- Electromagnetic counterpart follow up:
  - Preliminary detection from LIGO-Virgo.
  - 40 separate EM telescopes then turn.
  - [arxiv:1710.05833] (> 3500 authors).
- IceCube result combining high-energy neutrinos and blazar observations.

Radiation processes

- Next part of the lecture goes through various processes which are capable of generating electromagnetic observations.
- Covered in more detail in Minor topic: Structure formation in the Universe.
- A given process by detailed balance can in general contribute to either absorption or emission.
- Fundamentally radiation emission (and absorption) comes from accelerated charge.
- Characterised as Free-free, bound-bound, bound-free, free-bound.
- Thomson/Compton scattering (elastic/inelastic) of photon and electron.
- Recommend the book "Radiative processes in Astrophysics" by Rybicki and Lightmann.

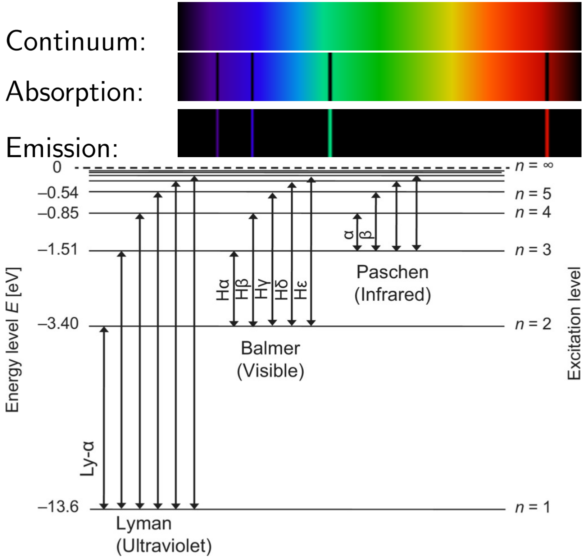
Relativistic mechanics and electromagnetism

- Can define the four-acceleration as the proper-time derivative of four-velocity $\boxed{a^\mu = \dot{u}^\mu.}$
- Note that four-acceleration and four-velocity are orthogonal (since $u^\mu u_\mu = \text{const}$).
- It is sometimes helpful to define a "four-force" such that $f^\mu = ma^\mu$, although this can sometimes be unintuitive in comparison to the three-force (due to it's orthogonality with four-velocity).
- For electromagnetism the three-force in the Newtonian case is $F = e(E + v \times B/c)$.
- Noting that the field strength tensor is

$$F^{\mu\nu} = \begin{pmatrix} 0 & -E_x/c & -E_y/c & -E_z/c \\ E_x/c & 0 & -B_z & B_y \\ E_y/c & B_z & 0 & -B_x \\ E_z/c & -B_y & B_x & 0 \end{pmatrix}.$$

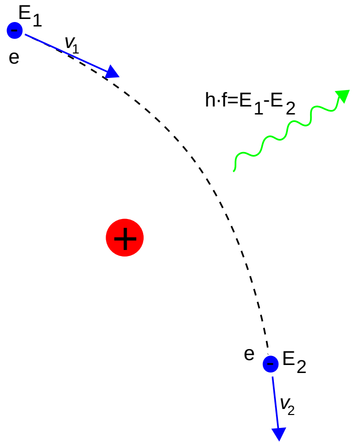
- We see that we can identify the four-force with $\boxed{f^\mu = \frac{e}{c} F^\mu_\nu u^\nu}$ which satisfies $f^\mu = m\dot{u}^\mu$.

Line radiation (bound-bound)



- Measured using spectroscopy.
- Most important in visible, IR and UV, as energy scales defined by difference in electronic orbitals.
- Also see emission/absorption lines in lower frequency measurements from e.g. nuclear spin flip transitions.
- Note that in astronomy many "forbidden" transitions (i.e. ones that cannot be seen in terrestrial labs) become important, e.g. HI lines for radio astronomy.

Bremsstrahlung (free-free)



- Radiation produced by deceleration of charge in matter (German for "Braking radiation").
- Occurs for cataclysmic processes such as Supernovae/shocks.
- The Larmor formula states a charge q with acceleration a has Power $\boxed{P = \frac{q^2 a^2}{6\pi\epsilon_0 c^3}.}$
- In relativistic covariant form $\boxed{P = -\frac{q^2 \dot{u}_\mu \dot{u}^\mu}{6\pi\epsilon_0 c^3}}$, i.e. $\frac{q^2\gamma^4}{6\pi\epsilon_0 c^3}\left(\dot{\beta}^2 + \frac{(\beta\cdot\hat{\beta})^2}{1-\beta^2}\right)$.
- Energy spectrum (frequency dependence) is continuous, whose peak location is proportional to $E_1 - E_2$, so can occur anywhere, but processes that typically produce it and reach us are in the X-ray band.

Synchrotron radiation

- Charged particles in a magnetic field move in helices.
- Nonrelativistic case is termed *cyclotron*, relativistic case is termed *synchrotron*.
- Relativistic equations are (noting the cancellation of proper time factors on both sides)

$$\frac{d}{dt}(\gamma m v) = \frac{q}{c} v \times B, \qquad \frac{d}{dt}(\gamma m c^2) = \frac{q}{c} v \cdot E.$$

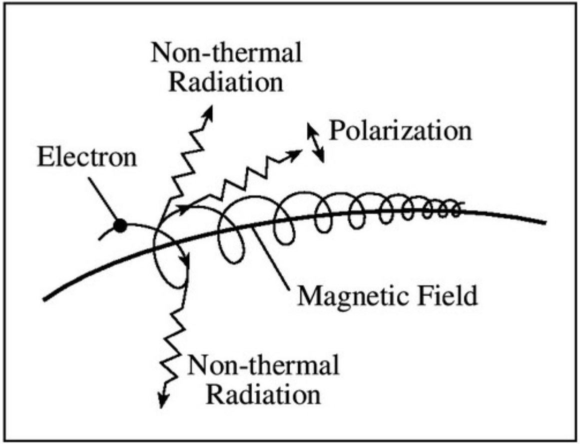
- If $E = 0$, then the second of these gives $\gamma = |v| =$ const, and therefore the first gives

$$m\gamma \frac{dv}{dt} = \frac{q}{c} v \times B.$$

- Separating into $v_\parallel$ and $v_\perp$ as usual gives

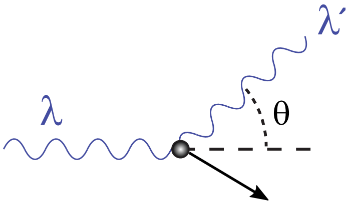
$$\frac{dv_\parallel}{dt} = 0, \qquad \frac{dv_\perp}{dt} = \frac{q}{\gamma m c} v_\perp \times B.$$

- i.e. helical motion with $|v_\parallel|$, $|v|$ and $v_\perp$ constant, and gyration frequency $\boxed{\omega_B = \dfrac{qB}{\gamma m c}}$.



- Since the acceleration $a_\perp$ is perpendicular to $v_\perp$, with magnitude $a_\perp = \omega_B v_\perp$, from the Larmor formula $P = \frac{e^2\omega_B^2 v_\perp^2}{6\pi\epsilon_0 c^3}$.
- To derive expressions for the synchrotron radiation frequency, one needs to take into account relativistic beaming which then gives $\omega \sim \gamma^3\omega_B$, and therefore $\sim 10\gamma^2 B$ GHz (where the 10 comes from including all the constants and extra effects like gyration broadening and averaging – see 6.2 of Rybicki & Lightmann).
- We therefore expect that even very strong magnetic fields are in the radio band.
- Note that beaming greatly increases the range of synchrotron radiation.
- It is also generally polarised.

Compton scattering



- Note that Thomson scattering is the non-relativistic limit of Compton scattering (i.e. assuming changes to photon momentum are negligible, and no frequency change in photon).
- The initial and final photon and electron four-momenta are

$$p_\gamma = \frac{E}{c}(1, n) \quad p'_\gamma = \frac{E'}{c}(1, n') \qquad p_e = (mc, 0) \quad p'_e = (\varepsilon/c, p).$$

- Conserving energy and momentum $p_\gamma + p_e = p'_\gamma + p'_e$, rearranging & squaring, eliminating the final electron momentum and using $\cos\theta = n \cdot n'$ gives:

$$E' = \frac{E}{1 + \frac{E}{mc^2}(1 - \cos\theta)} \qquad \Rightarrow \qquad \lambda' - \lambda = \frac{h}{mc}(1 - \cos\theta), \qquad \frac{\Delta E'}{E} = -\frac{E}{mc^2}.$$

- $\lambda_c = \frac{h}{mc} \sim 2.43$pm is the Compton wavelength of the electron.
- So for $\lambda \gg \lambda_c$ (i.e. gamma rays) we can expect Compton scattering.

Inverse Compton scattering

- The previous picture changes if electrons are moving (i.e. if you transform the frame).
- Details can be quite complicated, but broadly the photon can gain energy from thermal electrons
$$\frac{\Delta E'}{E} \sim \frac{v_e^2}{c^2} = \frac{4kT}{m_e c^2}.$$
- This can have an effect for lower frequencies than Gamma-rays, so is generally as or more important than Compton scattering.
- Also worth noting that in compact sources these effects can combine in e.g. synchro-self-Compton radiation where Compton scattering of synchrotron radiation creates additional limits (e.g. the Klein-Nishin cutoff means that the brightness temperature $T_B < 10^{12} K$).

Pair production

- Electron-positron pairs form when photons collide at energies $> m_e c^2 = 511\,\mathrm{keV}$.
- In a relativistic thermal gas, energy injected goes into the rest mass of new particles rather than kinematics, which means that at $500\,\mathrm{keV}$ the $e^{\pm}$ quickly annihilate.
- At high enough temperatures however, pair production outweighs annihilation.
- For photon photon collisions $\gamma + \gamma \to e^{\pm}$ requires $E_\gamma^{(1)} E_\gamma^{(2)} > 2 m_e^2 c^4$, so e.g. require two MeV photons, or a TeV photon and an infrared photon.
- For a source of radius R with luminosity L, the probability that a photon will collide with another is given by the optical depth $\tau_{\gamma\gamma} \sim n_\gamma \sigma_T R$, and since $n_\gamma = \frac{L}{4\pi R^2\, c\, 2 m_e c^2}$, this gives $\tau_{\gamma\gamma} \sim \frac{L}{R} \frac{\sigma_T}{m_e c^3} = l$, where l is a dimensionless compactness parameter of the source.
- For $l \gg 1$, significant pair production occurs, and we call such a highly luminous source of soft γ-rays which is rapidly varying compact.

Summary

- Astronomy utilises the whole of the electromagnetic spectrum.
- In recent years we have gone beyond this (gravitational waves and neutrinos).
- The future is bright, with some phenomenal instruments taking "first light" over the course of your prospective research careers.
- Concepts to be aware of
  - Line radiation,
  - Bremsstrahlung (free-free),
  - Synchrotron radiation,
  - (Inverse) Compton scattering,
  - Pair production.
- Recommend the book "Radiative processes in Astrophysics" by Rybicki and Lightmann.

Next time

Accretion disks