Measuring the mass density and geometry of the universe with supernovae—11 Feb 2010

- Test
  - Tues, 16th
  - One cheat sheet
  - Content: Classes through Feb 2nd. Does not cover RW metric. Homework 1–3.
  - Missouri "Show me" Club today.
- What are the dimensionless parameters of the universe?
  - H_0 is not dimensionless
  - $\Omega_0 = \frac{8\pi}{3} \frac{G\rho}{H_0^2}$
- Measurement of the flux of supernovae. Big surprise. $\Omega_{vac} \neq 0$.
- Radiation
- The cosmological constant
- Measuement of the angular size of fluctuations in the cosmic microwave background radiation.

Flux of a standard candle

A supernova emits luminosity $L(f)$ $[J/s/\mathrm{Hz}]$. What is the flux F $\left[J/\mathrm{s}/\mathrm{m}^2/\mathrm{Hz}\right]$ that we receive on earth?

Why does the relationship between luminosity and flux depend on the metric?
Give an example where it clearly depends on the metric.

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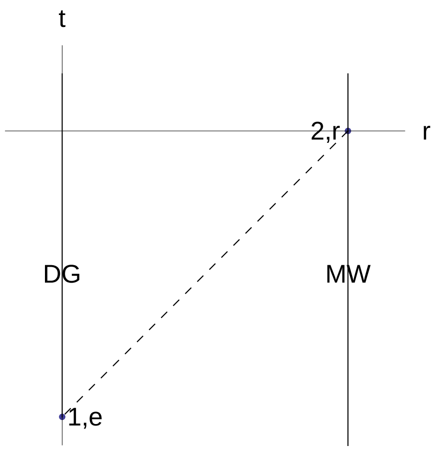

Caption: A distant galaxy emits a burst of photons over time $d\,t_e$ in a frequency band $d\,\nu_e$.

The total number of photons in the burst is

$$N = \frac{1}{h\,\nu_e} L(\nu_e)\, d\,t_e\, d\,\nu_e \quad .$$

We receive some number of photons, the ones that go into our detector of area A. The area of our detector is (from the metric)

$$A = (a\,r\,d\,\theta)\,(a\,r\,d\,\phi).$$

What do I use for a? a for supernova or a of astronomer?

Our detector subtends a solid angle of $\frac{A}{r^2}$, we catch

$$N\,\frac{1}{4\,\pi}\,\frac{A}{r^2}$$

photons.

Q: These photons have energy $h\,\nu$. What is $\frac{\nu}{\nu_e}$?

Q: These photons are spread out in time $d\,t$ and in frequency $d\,\nu$. What is $d\,t$ compared with $d\,t_e$? What is $d\,\nu_e$ compared with $d\,\nu$?

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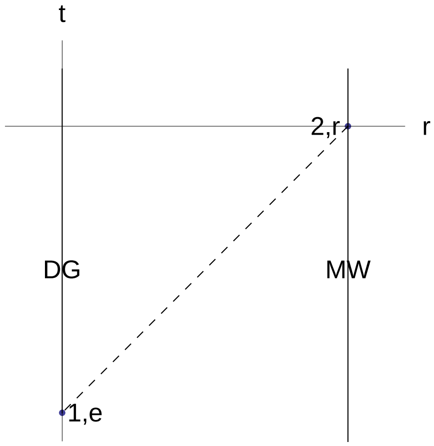

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We already figured out this question. The wavelength of light expands by the same factor as the universe. $d\,t$ behaves the same as wavelength, since $d\,t$ behaves as the time between emission of wave peaks. Therefore $\frac{d\,t_e}{d\,t} = a_e$. $\frac{\nu}{\nu_e} = a_e$. $\frac{d\,\nu_e}{d\,\nu} = a_e^{-1}$.

The flux is related to the number of photons that we caught by

$$F\,d\,t\,d\,\nu\,A = N\,h\,\nu\,\frac{1}{4\pi}\,\frac{A}{r^2}$$

$$F(\nu) = L(\nu_e)\,\frac{\nu}{\nu_e}\,\frac{1}{4\pi\,r^2}\,\frac{d\,t_e}{d\,t}\,\frac{d\,\nu_e}{d\,\nu}$$

The frequency of the photons that we catch are shifted from the frequency that was emitted.

$$\boxed{F(\nu) = L\left(\nu\,a^{-1}\right)\,\frac{a}{4\pi\,r^2}}$$

We drop the subscript on a_e since a is clearly the expansion parameter when the light was emitted. It is handier to think that r is the comoving coordinate of the source.

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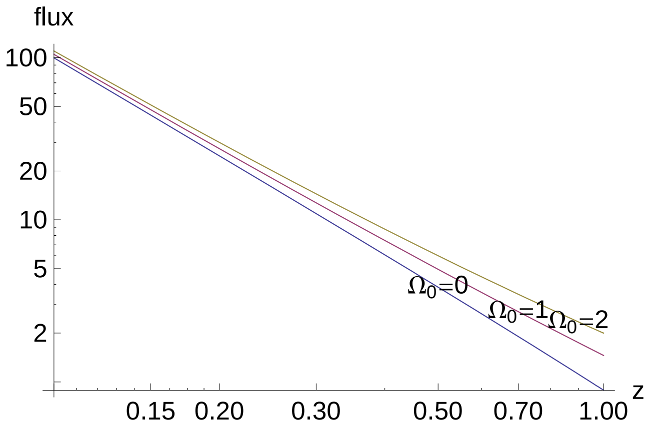
How does flux depend on the density parameter?



Caption: Flux vs redshift for three values of the density parameter.

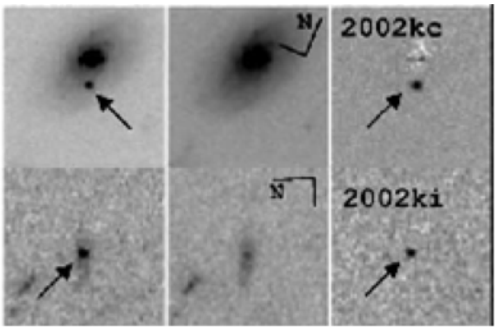
The flux

$$\boxed{F(\nu) = L\left(\nu\, a^{-1}\right) \frac{a}{4\,\pi\, r(a)^2}}$$

We have computed $r(a)$ for three cases with pressureless matter. By the same procedure, we can find $r(a)$ for radiation where $\rho \sim a^{-4}$ or the vacuum where ρ is a constant or for a mixture or all three.

Q: The supernovae are brighter for a universe with a higher mass density.
Why is the distance shorter? Since signals are photons, rephrase: Why is the time shorter for the universe to expand by a factor of 2 (from $z = 1$) for a universe with a higher mass density?

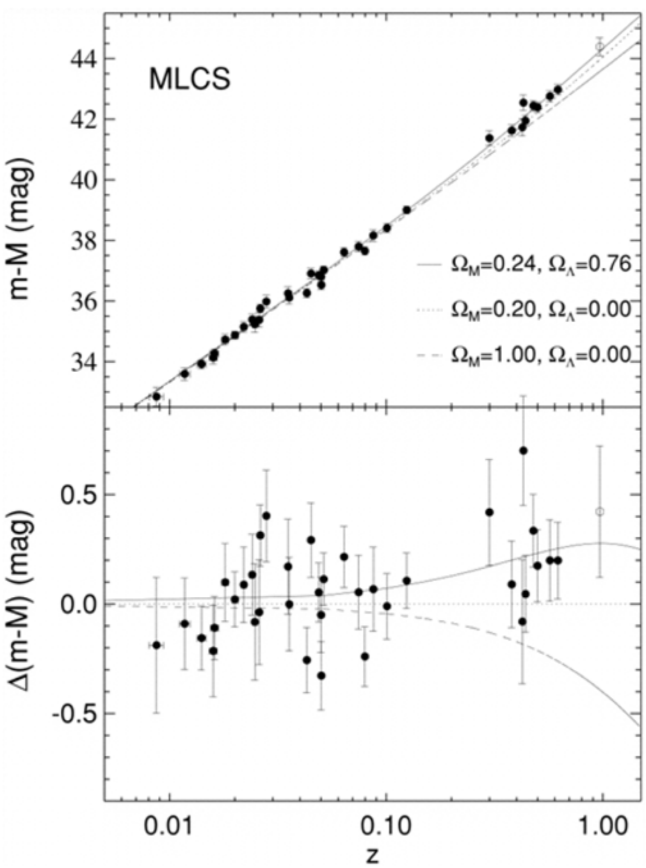
Measuring the flux of type I supernovae



Riess et al, 2004, ApJ 607, 665.

- Type I supernovae do not have hydrogen in the spectrum. Type I supernovae do have hydrogen.
- A Type II supernova is a massive star that explodes when it runs out of fuel and pressure is insufficient to counter gravity.
- A Type I supernova is a white dwarf that explodes.
  A WD and giant orbit each other.
  Mass moves from the giant to the WD.
  WD explodes when it gets so much mass from the giant that degeneracy pressure can no longer oppose gravity.
- Type I supernovae are "standard candles." They have the same luminosity.
- How to find supernovae
  Look at many galaxies.
  Look again later. Find objects that were not there earlier.
- Measuring the flux
  Measure the flux over time. Identify the peak flux and the rate of flux decrease.
  Report the peak flux corrected by an empirical correlation between peak flux and the rate of decrease.

Observations



Upper plot: magnitude of the flux compared with the flux at a distance of 10 pc.

$$m - M = -2.5 \log_{10} F / F(10\,\text{pc})$$

Lower plot: difference between $m - M$ and a model with $\Omega_0 = 0.2$ for pressureless matter.

Other models: $\Omega_{0,\text{matter}} = 1$, $\Omega_{0,\Lambda} = 0$ (Λ stands for cosmological constant or vacuum)

$\Omega_{0,\text{matter}} = 0.24$, $\Omega_{0,\Lambda} = 0.76$

Supernovae are fainter than that for a universe with 0.2 of the critical density. Recall: to put supernovae at a given redshift farther, remove mass from the universe to get universe to expand slower in the past. Reiss et al say supernovae are too faint even if there is no mass. Need the negative pressure of the vacuum to accelerate the expansion.

Conclusion:

The dominant component of the universe is the vacuum energy. Its density parameter is 3 times that of pressureless matter.