Astrophysics lab notes

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1 A-L laboratory

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$$\text{Lab Course} = \text{Course}(\lambda) \tag{1}$$

Objective of this course: *how to build an astronomical instrument* which will push the limits of astrophysical knowledge and technology.

1.1 Orders of magnitude

Diameters: in the future 24 m, 37 m.

Resolution: 0.04 arcsec for the HST.

Collected photons: 2700 Hz for an eye at $V = 6$.

For a galaxy at redshift $z = 10$, the Lyman (?) break at 91.4 nm is shifted.

In the background: magnitude 18 (with moon), 21 (no moon) per arcsec square.

10 meters, "seeing limited": 1 arcsec; 1 meter, "diffraction limited": 0.1 arcsec. Collection ratio: 100X, but the size of the background in which the unresolved source is located is also 100X.

We have a great school of *adaptive optics*.

1 October

http://people.na.infn.it/~barbarin/MaterialeDidattico/0-corso%20Fisica%20astroparticel
0-libro-longair.pdf

Slides are found at: http://www.thebotta.com/students/students.htm

Username: `stud`, Password: `stud_pd`.

Bisogna fare una presentazione sui dati che ci faranno analizzare e discuterla poi. Analisi dati al pc molto su dati di alte energie e raggi X, gamma in generale.

Parla dell'importanza degli interferometri LIGO e VIRGO; dei neutrini (Kamiokande, IceCube etc.); raggi cosmici, si incazza coi fisici che usano l'eV per misurare tutto lol. Insomma, le alte energie sono tutto nella vita per un ricercatore.

2 October

2 An introduction to X-ray astronomy

What are the sources for X-ray astronomy, beyond the Sun? Many binary systems in our galaxy, there is variability on the scales of milliseconds.

Also, galactic nuclei emit X-rays; also the gas trapped in the middle of clusters of galaxies is very massive.

Diffuse radiation also exists. We do not really know where it comes from.

On top of our atmosphere there is an *ionosphere*, which reflects our radio signals: we can communicate even when we are so far that the curvature of the Earth would prohibit it.

In the sixties, some people put Geiger counters on WWII V2 rockets, and someone actually put a directional sensor: this allowed people to discover the fact that the ionosphere was ionized by X-rays from the Sun.

In the 1960s Giacconi (the fast-moving one) and Rossi (the clever one) thought of a way to build a "telescope" for X-ray astronomy: with gold foil shaped into a section of a parabola we can focus the X-rays. This would allow people to see something but the Sun, like the moon or the Crab Nebula.

Giacconi founded his own company to build the thing.

They used an *anti-coincidence* shield: this allows us to distinguish (charged) cosmic rays from X-rays. This allowed Giacconi to find evidence for X-rays from beyond the solar system: PRL, 1962.

We can use lunar occultation in order to specifically figure out which source the X-rays come from. This was used with the Crab nebula.

In 1965 people discover the fact that X-ray sources can be variabile.

We can use collimators in order to select only a specific direction.

An interesting quantity to look at is the ratio of luminosities L_X / L_{optical}. For the Sun, this is of the order 10^{-6}. For Sco X-1 this is 10^3 (!)

If something is moving back and forth, we can use red and blueshift periodicity to figure out the periodicity of the system. With Kepler's law we can get a lower bound for the companion mass. This is done in the optical.

Compared to 1962 we have 10^9 better sensitivity, 10^5 better angular resolution, 10^4 better spectral resolution (now $E/(\Delta E) \sim 10^3$). Now we use X-ray CCDs, not Geiger counters.

8 October 2019

We visit https://heasarc.gsfc.nasa.gov

This is the archive where we will spend most of our time: one can find the data from all the current missions.

At the link http://adsabs.harvard.edu/abstract_service.html one can find Astrophysics papers, with full text sources.

There is the extragalactic database https://ned.ipac.caltech.edu/, and a galactic database at http://simbad.u-strasbg.fr/simbad/.

In https://heasarc.gsfc.nasa.gov one can go to Tools $\rightarrow$ Coordinate converter to find coordinates. If you look at an object and then at another it tells you what the angular distance between them is.

In Tools $\rightarrow$ energy converter you can convert energies.

Now, let us talk about *specific intensity*: it is defined as

$$I_\nu = \frac{\mathrm{d}E_\nu}{\mathrm{d}A\,\mathrm{d}\Omega\,\mathrm{d}\nu\,\mathrm{d}t\cos\theta} = \frac{h\nu\,\mathrm{d}N_\nu}{\mathrm{d}A\,\mathrm{d}\Omega\,\mathrm{d}\nu\,\mathrm{d}t\cos\theta} = nh\nu\,, \tag{2}$$

where n is the *photon intensity*.

We also define *flux density*, measured in $\mathrm{erg\,cm^{-2}\,Hz^{-1}\,s^{-1}}$:

$$F_\nu = \int_{\text{source}} I_\nu \cos\theta\,\mathrm{d}\Omega = \frac{\mathrm{d}N}{\mathrm{d}E} \tag{3}$$

and *flux*, measured in $\mathrm{erg\,cm^{-2}\,s^{-1}}$:

$$F = \int_{\nu_1}^{\nu_2} F_\nu\,\mathrm{d}\nu\ . \tag{4}$$

All detectors are just energy-dependents photon counters.

Sometimes, the flux density follows a power law: $F_\nu = kE^{-\Gamma}$.

2.1 The Earth's atmosphere

From Earth we can observe visible, near infrared & radio light.

Far infrared, long radio waves, and from ultraviolet onwards the light is blocked.

If z is the angle between the zenith and the observation angle, we say that we have $1/\cos z$ airmasses to see through. The intensity is:

$$I(z) = I_0 e^{-\tau} = I_0 e^{\tau_0 \sec z} \tag{5}$$

We can distinguish stars from planets: stars twinkle because of the seeing effect, while planets are extended for us so they do not.

9 October 2019

Clarification from last lecture. Dithering is caused by the fact that any single pixel in an X-ray CCD may be arbitrarily noisy, and if the telescope only looks at an astronomical object from a certain viewpoint without rotation a certain region of the object will always be imaged by the same pixel, therefore the errors between images will be correlated. So, we move our telescope around in order to have a certain region of the astronomical object be imaged by several uncorrelated pixels.

Normal distribution: the pdf is

$$\mathcal{N}(x;\mu,\sigma^2) = \frac{1}{\sqrt{2\pi\sigma^2}} \exp\left(\frac{-(x-\mu)^2}{2\sigma^2}\right). \tag{6}$$

Poisson distribution: the probability of getting m events if they happen independently at a rate λ is

$$\mathbb{P}(m;\lambda) = \frac{e^{-\lambda}\lambda^m}{m!}, \tag{7}$$

and it is easy to prove that for a Poisson distribution $\mu = \sigma^2 = \lambda$.

If the rate is, say, a temporal rate like $[\alpha] = \text{Hz}$ then we substitute $\lambda = \alpha t_{\text{obs}}$.

We discuss detectors: semiconductors, NP junctions.

We define the signal-to-noise ratio:

$$\text{SNR} = \frac{S}{\sqrt{S+B}} = \frac{S_{\text{ph}} t A W_b}{\sqrt{\left(S_{\text{ph}} + B_{\text{sky}}\right) t A W_b + Dt + R_N^2}}, \tag{8}$$

where $S = S_{\text{ph}} t A W_b$ is the (constant) signal photon count: t is the observation time, A is the telescope area, W_b is the bandwidth, and S_{ph} is the source photon intensity.

We must also account for the background B: it is caused by dark counts whose rate is D, by background photons whose intensity is B_{sky}, and by readout noise R_N^2.

We can define the detection threshold... This will be talked about next lecture.

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We come back to the signal-to-noise ratio. The SNR is dimensionless.

What happens to the SNR if we increase pixel size? It improves. However, if we normalize for the area the thing is different: D and R_N^2 go up with pixel size. Overall there is more noise with bigger pixels.

Background-limited instruments: if B is negligible then SNR $\propto \sqrt{F_{\rm src} t}$, if it is dominant then SNR $\sim (F_{\rm src}/F_{\rm bkg})\sqrt{t}$.

The *Quantum efficiency* is the fraction of photons we can detect. The human eye is around 1%, CCDs can get up to 90%.

A bit of lesson on telescopes, it can be found on the slides.

CHANDRA has good angular resolution while XMM has good spectral resolution.

INTEGRAL stops at 100 keV, Fermi starts at 100 MeV.

Now, *inverse Compton emission*. In the rest frame of the electron, which we will use throughout, it loses energy like

$$-\left(\frac{{\rm d}E}{{\rm d}t}\right)' = \sigma_T c U'_{\rm rad}\,, \tag{9}$$

where $U'_{\rm rad}$ is the energy density of radiation, while σ_T is the Thomson scattering cross section.

Depending on the temperature of the electrons, we can have regions with mostly Compton scattering or inverse Compton scattering:

$$\frac{\Delta E}{E_0} = \frac{4k_B T_e - E_0}{m_e c^2}\,, \tag{10}$$

depending on the sign of the numerator on the RHS we can see whether energy is transferred to or from electrons. This applies to a *single photon*: to get a description of the phole distribution we need the Kompaneets equation.

In the Kompaneets equation we impose $\partial n/\partial t = 0$, since n is frequency integrated and Compton scattering conserves photon number.

Now, follow the instructions in the slides. Open `ISGR-EBDS-MOD`: "all", you can then see the conversion of energy to channel.

The quantity measured in

$$\mathrm{keV}^2\Big(\mathrm{photon/cm^2/s/keV}\Big)\,, \tag{11}$$

describes the energy output of the source at each energy.