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 → 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 → 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.

Tue Oct 15 2019

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 $\propto \sqrt{F_{\text{src}} t}$, if it is dominant then SNR $\sim (F_{\text{src}}/F_{\text{bkg}})\sqrt{t}$.

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

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

where U'_{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

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

describes the energy output of the source at each energy.

Wed Oct 16 2019

Or galaxy might have had a jet perpendicular to it in the past.

Seeing galaxies at very high redshift is difficult: γ ray astronomy is useful that way, since it can tell very low FOV (optical?) telescopes where to look.

We look at different wavelengths detected for 3C 279: a blazar.

AGNs are Active Galactic Nuclei. They are best seen through X-rays, which can pierce the dusty accretion disc.

Iron is the final state of fusion: we expect to see iron lines near SMBHs. When looking at a BH accretion disc at a high inclination, we see the region *behind* the BH, since light is curved.

Mrk 876 iron line: it seems *too* reshifted, cosmological redshift alone does not explain it. We need to account for gravitational reshift from the SMBH, and tell what the distance from the center is.

Also, we can use Doppler redshift to measure the speed of rotation around the SMBH: how does this work? It seems like the two effects should combine…

About INTEGRAL: it has 4 instruments, a γ ray telescope, an X ray telescope, an optical monitoring camera (and...?).

It has a huge FOV (20° by 20°), but the angular resolution is only 12′.

We talk about the MeV gap.

Tue Oct 22 2019

[Missing. To recover.]

Wed Oct 23 2019

[Missing. To recover.]

Tue Oct 29 2019

In the second part of the course we will look at a certain dataset in groups, analyze it, research it (with a couple weeks or a month to do it); then do a presentation for around 10 minutes each.

The exam can be done even the last lecture: we just have to notify him a week in advance.

We will analyze data either from CHANDRA or NUSTAR.

Exercise: best fit in the 3 to 79 keV and plot spectrum $E^2 \frac{\mathrm{d}N}{\mathrm{d}E}$. Verify that the parametrs of the centroid of the iron line and the temperature are independently derived. Verify that the iron line is statistically significant.

Steppar: to create a contour plot.

Wed Oct 30 2019

Line emission: the light from the corona illuminates the accretion disk, and we see the spectral lines from the various elements in it.

When looking at a disk edge-on, we have several effects: we see

1. Doppler shift (Newtonian): the outer annulus has a faster tangential velocity since the accretion disk rotates approximately rigidly;
2. Beaming (special relativistic);
3. Transverse Doppler (special relativistic);
4. Gravitational redshift (general relativistic).

We can simulate the spectra due to a line emission at different angles with respect to the accretion plane, and with respect to either a Schwarzschild or Kerr BH.

Exercise.

We assume that the matter in the accretion disk basically orbits in circular paths, regulated by

$$\frac{v^2}{r} = \frac{GM}{r^2}\,, \tag{12}$$

with energy given by

$$E = \frac{1}{2}mv^2 - \frac{GmM}{r}\,. \tag{13}$$

We get the luminosity of the disk by assuming that the heat is dissipated through viscosity,

$$L = \int_{r_*}^{\infty} -\frac{\mathrm{d}E}{\mathrm{d}T} 2\pi r \,\mathrm{d}r = \frac{G\dot{m}M}{2r_*}\,, \tag{14}$$

where T is time, and $\dot{m} = \mathrm{d}m/\mathrm{d}T$.

The temperature is increasing as r decreases. The total spectrum is the sum of several blackbodies, at each temperature.

Instead, we see a blackbody component, and a powerlaw coming from the reflection of the accretion disk, plus an iron line.

Tue Nov 05 2019

We start by analyzing the data from CHANDRA.

Then, we start to talk about *grazing angles*: they depend on δ, where

$$\delta \sim \frac{1}{2\pi} N_e r_e \lambda^2\,, \tag{15}$$

which is of the order of one degree, and allows us to build detectors with more effective area.

The effective area is:

$$A_{\text{eff}} = A_{\text{geom}} R(E) V(E, x, y) Q(E, x, y) \,. \tag{16}$$

The vignetting V accounts for the fact that the outermost pixels are less bright than the innermost ones; the quantum efficiency Q is...

Wed Nov 06 2019

Presentation by Bottacini like we will do for the exam.

Tue Nov 12 2019

Today we will start with 20′ of lectures, then research. This will be the same for a few lectures onwards.

Chandra data can be retrieved at `https://cda.harvard.edu/chaser`.

Both CHANDRA and XMM-Newton are *huge*. CHANDRA is optimized to do images (good angular resolution), while XMM-Netwon has a much better spectral resolution.

CHANDRA has 4 nested shells, which limit the background noise B in

$$SNR = \frac{S}{\sqrt{S + B}} \,, \tag{17}$$

on the other hand, we can increase S: we make the effective area larger. XMM has three telescopes, each of which 58 shells: a total area of $120\,\text{m}^2$.

The PSF FWHM is 0.5 arcsec. PSF means "Point Spread Function": the response of the detector to a Dirac delta.

For each pixel, we have a possibility of the equal photons getting in our detector at the same time: they are then detected as having double the energy. This makes the spectrum seem harder. This can be fixed by looking at a source off-axis if it is very bright.

Usually we look at a circle around the source which encloses 80% of the power emitted.

All of these effects are encoded in the `arf`: the Ancillary Response File.

The information of the channel-to-energy conversion and the spectral resolution will be taken care of by the: Redistribution Matrix File (rmf).

Evaluation criteria: content, presentation, language, knowledge.

We are given an envelope, which gives us the observation ID from CHANDRA: that gives us the group number also.

Our ID is 2121, the group number is 3.

The object is http://simbad.u-strasbg.fr/simbad/sim-id?Ident=MCG-5-23-16

Different wavelengths http://cdsportal.u-strasbg.fr/?target=ESO%20434-40

Title The reprocessing features in the X-ray spectrum of the NELG MCG -5-23-16 Authors Balestra, I.; Bianchi, S.; Matt, G. Bibcode 2004A&A...415..437B Abstract We present results from the spectral analysis of the Seyfert 1.9 galaxy MCG -5-23-16, based on ASCA, BeppoSAX, Chandra and XMM-Newton observations. The spectrum of this object shows a complex iron Kα emission line, which is best modeled by a superposition of a narrow and a broad (possibly relativistic) iron line, together with a Compton reflection component. Comparing results from all (six) available observations, we do not find any significant variation in the flux of both line components. The moderate flux continuum variability (about 25% difference between the brightest and faintest states), however, does not permit us to infer much about the location of the line-emitting material. The amount of Compton reflection is lower than expected from the total iron line EW, implying either an iron overabundance or that one of the two line components (most likely the narrow one) originates in Compton-thin matter.

Title The Cores of the Fe Kα Lines in Active Galactic Nuclei: An Extended Chandra High Energy Grating Sample Authors Shu, X. W.; Yaqoob, T.; Wang, J. X. Bibcode 2010ApJS..187..581S Abstract We extend the study of the core of the Fe Kα emission line at 6.4 keV in Seyfert galaxies reported by Yaqoob & Padmanabhan using a larger sample observed by the Chandra high-energy grating (HEG). The sample consists of 82 observations of 36 unique sources with z < 0.3. Whilst heavily obscured active galactic nuclei are excluded from the sample, these data offer some of the highest precision measurements of the peak energy of the Fe Kα line, and the highest spectral resolution measurements of the width of the core of the line in unobscured and moderately obscured (N H < 1023 cm-2) Seyfert galaxies to date. From an empirical and uniform analysis, we present measurements of the Fe Kα line centroid energy, flux, equivalent width (EW), and intrinsic width (FWHM). The Fe Kα line is detected in 33 sources, and its centroid energy is constrained in 32 sources. In 27 sources, the statistical quality of the data is good enough to yield measurements of the FWHM. We find that the distribution in the line centroid energy is strongly peaked around the value for neutral Fe, with over 80% of the observations giving values in the range 6.38-6.43 keV. Including statistical errors, 30 out of 32 sources (94%) have a line centroid energy in the range 6.35-6.47 keV. The mean EW, among the observations in which a non-zero lower limit could be measured, was 53 ± 3 eV. The mean FWHM from the subsample of 27 sources was 2060 ± 230 km s-1. The mean EW and FWHM are somewhat higher when multiple observations for a given source are averaged. From a comparison with the

Hβ optical emission-line widths (or, for one source, Brα), we find that there is no universal location of the Fe Kα line-emitting region relative to the optical broad-line region (BLR). In general, a given source may have contributions to the Fe Kα line flux from parsec-scale distances from the putative black hole, down to matter a factor 2 closer to the black hole than the BLR. We confirm the presence of the X-ray Baldwin effect, an anti-correlation between the Fe Kα line EW and X-ray continuum luminosity. The HEG data have enabled isolation of this effect to the narrow core of the Fe Kα line.