Lecture 7:
X-Ray and Gamma-Ray Imaging in 2D

Contents

Sources of X-Rays and Gamma Rays

Radiation

High-energy electromagnetic radiation, two non-disjoint notions.

- *X-rays:* high-energy electromagnetic radiation;
  wavelengths between $10\,\mathrm{nm}$ (*soft X-rays*) and $1\,\mathrm{fm} = 10^{-6}\,\mathrm{nm}$ (*ultra-hard X-rays*)
- *gamma rays:* wavelengths below $10\,\mathrm{pm} = 0.01\,\mathrm{nm}$ (no lower bound).
- X-ray photons are generated by energetic electron processes, gamma rays by transitions within atomic nuclei.

Sources of X-Rays and Gamma Rays (2)

Interaction with Matter

- usually less absorbed by matter than other electromagnetic waves
- Nevertheless, absorption is dominant interaction:
  Reflection and refraction are very weak.
- high ability to penetrate matter (provide information from inside objects)
- High energy causes potential damage when absorbed in biological tissue.
- difficult to manipulate

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Sources of X-Rays and Gamma Rays (3)

X-Ray Tube

- A strong electrical field accelerates electrons from anode which then hit a target (e.g. molybdenum, tungsten (Wolfram)).
- Spectrum consists of two parts:
  - *continuum part* characterised by cut-off wavelength $\lambda_{\min}$, maximum at ca. $1.5\lambda_{\min}$;
    created by the deceleration of the electrons
  - *characteristic part* formed by specific peak wavelengths;
    created by electron transitions within atoms (discrete energy levels)

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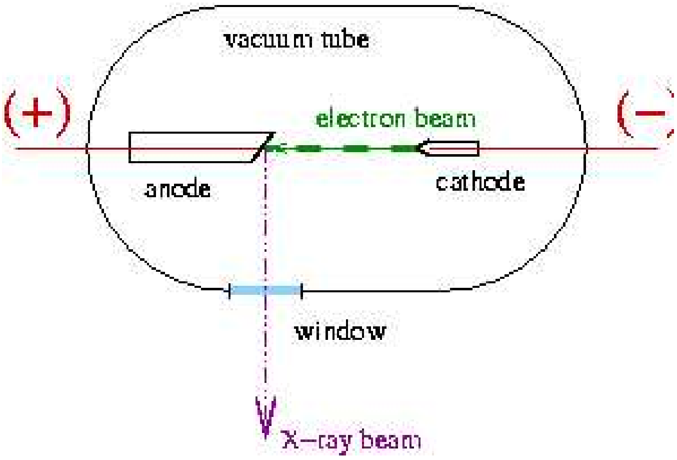
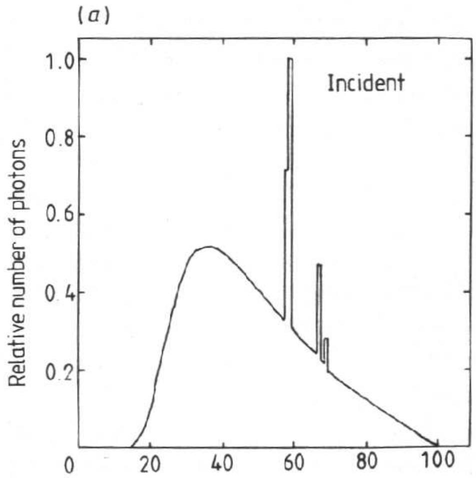
Sources of X-Rays and Gamma Rays (4)



X-ray tube (schematic).



Spectrum of an X-ray tube with tungsten target. *(Birch et al., 1979/Dance, 1988)*

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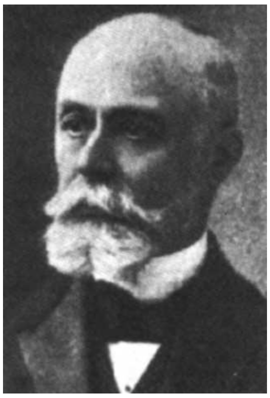
Sources of X-Rays and Gamma Rays (5)

Other Sources

- **Synchrotron radiation.** Electrons which are deviated by strong magnetic fields (see Maxwell's equations) emit X-ray radiation.
- **X-ray lasers.**
- **Radioactive decay.** In some types of radioactive decay, gamma rays are emitted.

Historical Remarks

Wilhelm Conrad Röntgen (1845–1923).



Henri Becquerel (1852–1908).

Pierre Curie (1859–1906).

Marie Curie (1867–1934).

All images: Spektrum-Verlag 1999.

Wilhelm Conrad Röntgen discovered X-rays in 1895.
Henri Becquerel discovered natural radioactivity in uranium in 1896.
Pierre and Marie Curie further investigated radioactivity after 1896 and discriminated alpha (Helium kernels), beta (electrons, positrons) and gamma rays.
All received Nobel Prizes for Physics, in 1901 (Röntgen) and 1903 (Becquerel, Curies).

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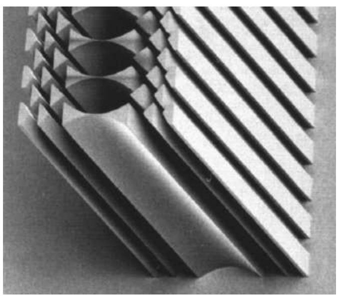
X-Ray Optics

- Reasonable amounts of reflected X-rays are achieved only for very acute angles.
- used in specific combinations of paraboloid and hyperboloid mirrors for X-ray astronomy (so-called Wolter mirrors).
- Since X rays are even more difficult to refract than to reflect, X ray lenses are still in their infancy.



Cylindrical X-ray lenses made of plastics.
(Forschungszentrum Karlsruhe, Spektrum der Wissenschaft, 2/2005.

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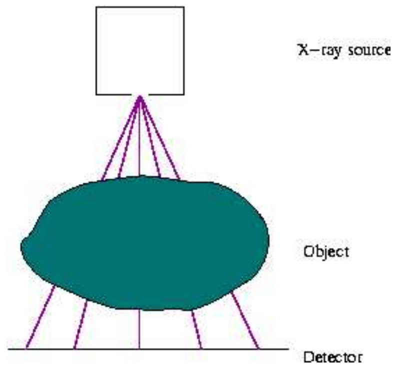
Transmission Radiography

- established method for 2-D imaging using X-rays
- applied in medical imaging as well as in material sciences
- does not rely on refraction or reflection of X-rays, just on absorption
- X-rays are sent straightly from the source to the detector through the object to be inspected.



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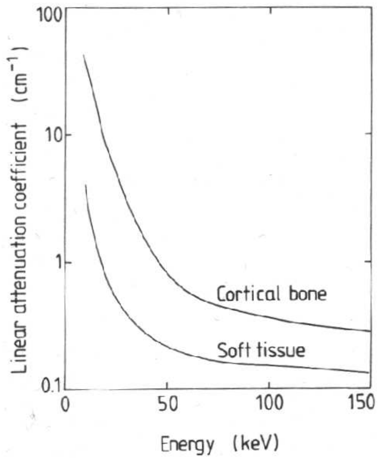
Attenuation

- Absorption together with other processes (like diffraction) in tissue or other objects to be examined *attenuates* radiation (cf. Lecture 3).
- The received energy is therefore

$$I(x, y) = N\,\varepsilon(E)\,E\,\exp\left(-\int \mu(x, y, z)\,\mathrm{d}z\right) + \text{scatter}$$

  N: the number of incident photons
  E: energy of the photons
  μ: attenuation coefficient, expressing absorption in matter
  ε: an efficiency function.
  The integral runs over the way from radiation source to detector.

- Scatter acts as a perturbation which degrades contrast in the image.
  In the simplest case, it is taken as slowly varying (in space) and thus a low frequency perturbation.
  It is strongest in the image centre.



Linear attenuation coefficient depending on energy for two types of tissue. *(Dance, 1988)*

- The attenuation coefficient μ varies approximately with the 4th power of the atomic number, and with -3rd power of E.
  Consequently, soft tissues absorb much less energy than bones (with "heavy" Calcium constituents).
- Too soft radiation is mostly absorbed in tissue without use for image acquisition.
  Thus it is filtered out by aluminium or copper filters.
  This filtering involves a tradeoff between contrast and dose.

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Detectors in Transmission Radiography

X-Ray Film

- Direct exposure X-ray film
  - creates sharp image
  - however, low absorption efficiency in diagnostic energy range
- Screen-film combinations with fluorescent screens allow for higher sensitivity (speed) because visible or UV photons account for the film blackening.

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Transmission Radiography (5)

Image Intensifier

- tube with fluorescent screen at input side
- X rays create flourescence
- a photocathode creates electrons
- electrons are focused in an electrical field and imaged at an output phosphor
- high photon gain (about 200 light photons for one incident X-ray photon)

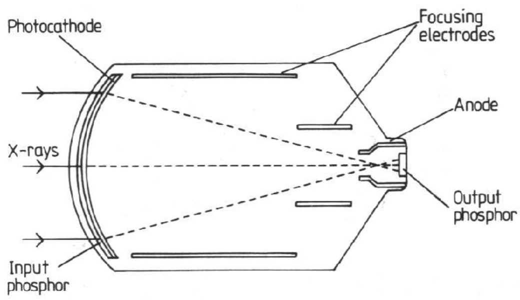
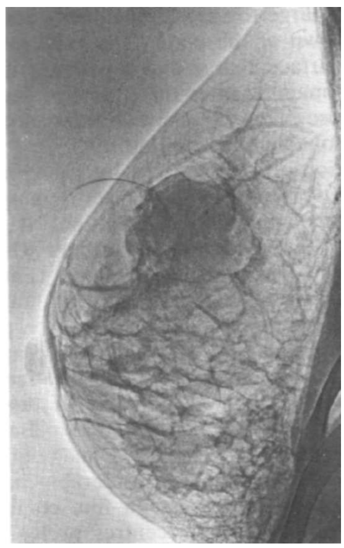


Image intensifier. *Image: Dance, 1988*

Transmission Radiography (6)

Xeroradiography

- Xeroradiography leads to paper images.
- works similar to xero(photo)graphy (Lecture 4): A charged selenium layer is discharged by photocurrent (caused by electron-hole pairs).
- creates sharp analog images



Xeroradiography.
Image: Dance, 1988

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Transmission Radiography (7)

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Practical Issues

Intensity of Radiation

- High-energy radiation can cause *damage in tissues* (and also in other objects under inspection). It is therefore necessary to keep the dose low.
- *Adaptation of X-ray spectrum* to the objects to be imaged helps to reduce dose. The spectrum should ideally contain only energies that give a high contrast for the objects of interest.
  Example: Tungsten spectra are useful for thicker body sections.
  Molybdenum, giving softer radiation, allows for high contrasts in thinner tissue.
- Sensitive detectors help in reducing dose.
  Tradeoff: Sharpness $\longleftrightarrow$ Dose Reduction.
- Scatter and background (diffuse radiation from outside the imaging system) cause noise. Tradeoff: Low Noise $\longleftrightarrow$ Dose Reduction.
- Modern systems operate close to the physical limits (only a few photons give one bit of image information).

Transmission Radiography (8)

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Contrast Media

- Some structures in the body can not easily be detected according to just X-ray intensity values.
- In some cases, a radiopaque (i.e. radiation blocking) material is used as *contrast agent* allowing to show these structures at higher contrast. This is necessary e.g. for imaging human stomach.

Transmission Radiography (9)

Examples

Analog radiography images generated by X-ray transmission. Left: human foot in two positions, right: human vertebra seen from the side (partial view)

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Transmission Radiography (10)

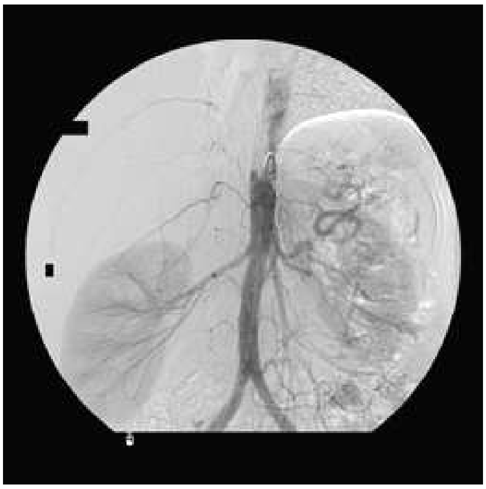
Examples

X-ray radiograph of a human shoulder with fracture.

X-ray radiograph of a hip with hip replacement.

(Images: http://hshs.mohawkcollege.ca/MedRadSci/RAD/radiography.htm)

Examples



X-ray angiography of kidneys. Blood vessels are filled with contrast agent.

X-ray radiograph of a stomach with barium contrast agent.

(Images: http://hshs.mohawkcollege.ca/MedRadSci/RAD/radiography.htm)

Emission Radiography

Principle of Emission Radiography

- imaging method in which the object itself (typically some parts of the human body) emits high-energy radiation which is then detected.
- This is achieved by injecting a radioactive isotope (short: radionuclide) which propagates in certain organ systems, and observing the distribution of emitted gamma radiation.
- Information is impressed on the radiation already during its emission.
- Absorption is not used for imaging.
- Like transmission radiography, emission radiography does not use reflection or refraction.

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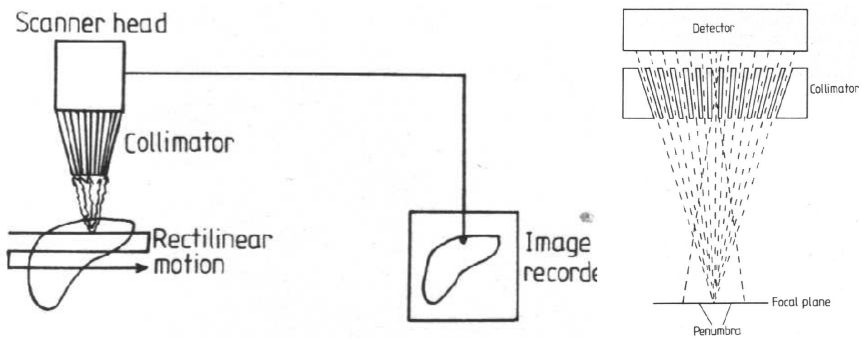
Detection

Rectilinear Scanner

- consisting of *collimator* and *detector*
- collimator narrows the rays



Rectilinear scanner and collimator *(Ott et al./Webb 1988)*

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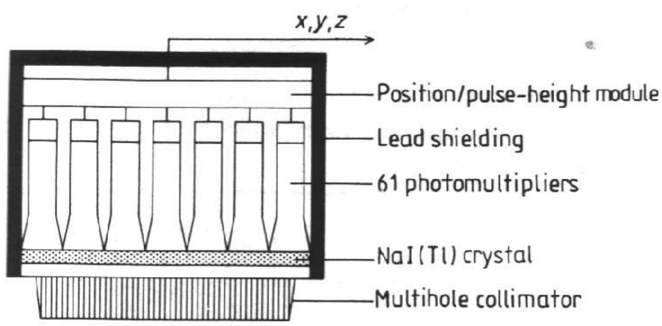
Gamma Camera

- consisting of a *multi-hole collimator* (often parallel-hole collimator), *scintillator* (a crystal which emits visible light on incidence of gamma rays), *photomultipliers* which amplify signals by "multiplying" incident photons) and detectors.



Gamma camera *(Ott et al./Webb 1988)*

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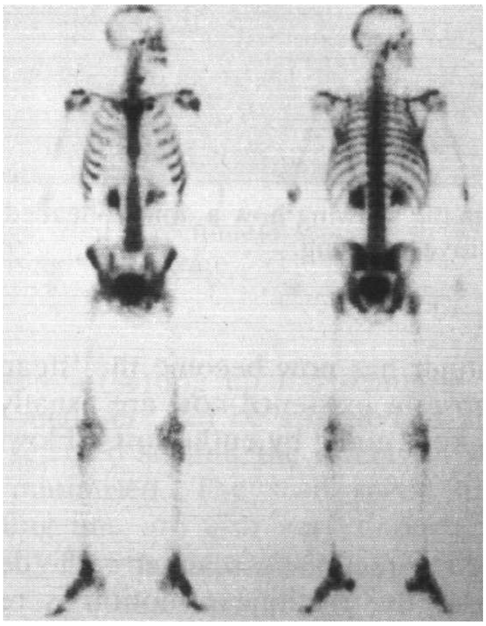
Example



Emission radiograph of entire human body.
(Ott et al./Webb 1988)

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Practical Issues

- Emission radiography with gamma-emitting radionuclides is also known as *scintigraphy*.
- Typical fields of application are thyroid diseases (Schilddrüsenerkrankungen).
- Doses are kept small by injecting radionuclides in low concentrations.
- Radioactivity in the body decreases after the treatment by two effects:
  - decay rate of the radionuclides, expressed by *physical half-life* T_{ph}
  - removal by metabolism, expressed by *biological half-life* T_{bio}.

  The *effective half-life* T_{eff} is given by

$$\frac{1}{T_{\text{eff}}} = \frac{1}{T_{\text{ph}}} + \frac{1}{T_{\text{bio}}} .$$

- Today, most radionuclides used have (physical) half-lifes in the order of magnitude of hours or a few days.
- Another important criterion is that the gamma rays emitted are of an energy which is absorbed as little as possible in tissue.

X-Ray Astronomy

Satellite-Based X-Ray Observatories

- Many astronomical objects emit X-ray radiation that can be imaged to study these objects.
- X-rays from space can't penetrate the earth's atmosphere down to ground.
- X-ray astronomy is made possible by satellite-based observatories.
  - *Chandra* launched July 23, 1999 by NASA.
  - *XMM-Newton* launched December 10, 1999 by ESA.
  - about half a dozen other missions.

X-ray telescope mirror of XMM-Newton consisting of 58 Wolter mirrors. *(Image: ESA.)*

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Observed Objects

The following list is incomplete.

- Sun (corona, i.e. outer atmosphere)
- planets (weak X-ray radiation)
- comets
- centre of Milky Way
- Pulsars/neutron stars and black holes
- X-ray novae (double-star system involving neutron star)
- gamma-ray bursts (GRB), e.g. with supernova explosions
- supernova remnants
- quasars (rotating hot gas disk around massive black hole, in galaxy centres)
- active galaxies

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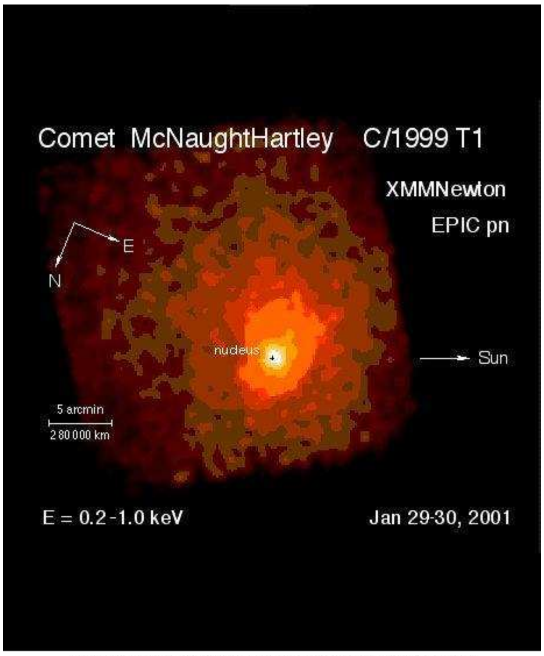
X-Ray Astronomy (3)

Example



Comet McNaught-Hartley observed with EPIC-pn

Image courtesy of MPE, Garching, Germany — European Space Agency

XMM-Newton X-ray image of comet McNaught-Hartley (C/1999 T1).
Image courtesy of MPE Garching, Germany and ESA – Measurements: B. Aschenbach

X-Ray Astronomy (4)

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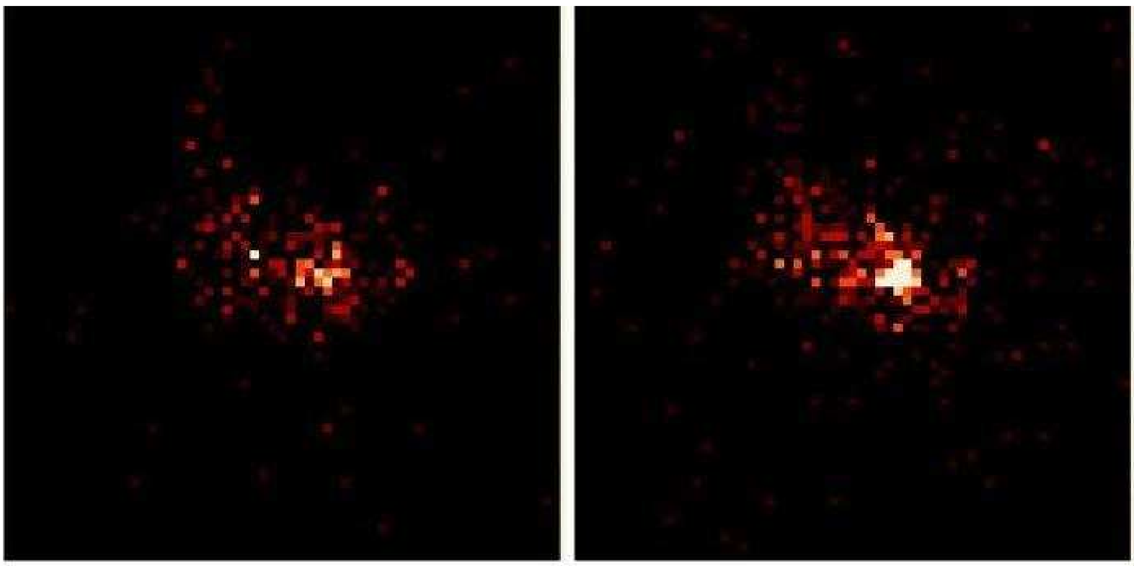
Example



X-ray Flare in the Galactic Nucleus

European Space Agency

X-ray flare in the galactic nucleus (centre of Milky Way), detected with XMM-Newton. **Left:** before the event, **right:** after. Each image has an exposure time of $1000\,\mathrm{s}$.
Image courtesy of A. Goldwurm, CEA Saclay and ESA – Measurements: A. Goldwurm et al.

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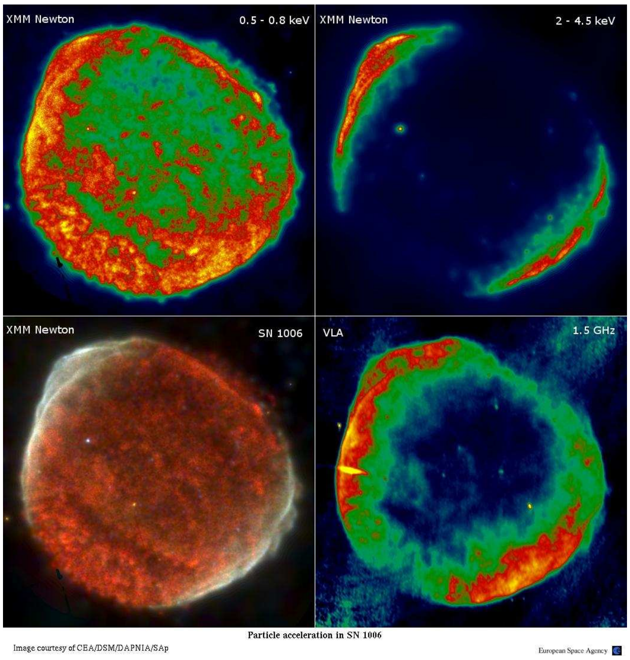
Example



Remnant of the supernova observed in the year 1006, as measured by XMM-Newton in the X-ray range, except for bottom right which is a radio-wave image for comparison. All images are false-colour images, taken in different frequency bands. Each of them reveals another kind of structure.

Image courtesy of CEA/DSM/DAPNIA/SAp and ESA – Measurements: Ballet, Jean

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Summary

- X rays and gamma rays are high-energy electromagnetic radiation.
- Absorption is the main interaction with matter.
  Reflection and refraction are less important.
- Transmission radiography images objects by exploiting their absorption characteristics.
- Detection may use fluorescence and photoelectric effects.
- In order to avoid tissue damage, a careful adaptation of the X ray spectrum is useful.
- Emission radiography is based on injecting radionuclides.
  It does not rely on absorption.
- Example: scintigraphy for imaging the thyroid.
- X ray astronomy is satellite-based and is used in numerous ways.

References

- S. Webb, *The Physics of Medical Imaging.* Institute of Physics Publishing, Bristol 1988.
- W. Greulich, editor, *Lexikon der Physik in sechs Bänden* (in German). Spektrum, Heidelberg 1998.
- ESA web pages (ESA home page, XMM-Newton home page)