THE PHYSICS OF GAMMA-RAY SOURCES

by Roland Diehl

SUMMARY

Observations of gamma-rays from objects and processes in the universe have become feasible during the past three decades, through advanced skills from high-energy laboratory physics and from space technology. These allow us to explore violent processes in the universe, which often escape detection at lower-energy radiation. Typical source processes are the collisions of energetic particles in cosmic radiation with gas, the radioactive afterglow of new-element formation, and matter-antimatter annihilation. Objects of astrophysical studies in the gamma-ray domain are the nuclei of active galaxies which most likely host massive black holes, accretion phenomena in the vicinity of compact stars or black holes, violent nuclear fusion events in novae and supernovae, and gamma-ray bursts which may be an extreme example of these. We have learned that acceleration of particles appears very efficient near such compact objects, but also in shock regions around massive stars. We have proven the paradigm of new-element formation inside stars and supernovae. Next steps are underway to study source emission details over wide ranges of the electromagnetic spectrum, in order to develop a more complete picture of these unusual and not well-understood physical processes.

WHY DO WE TALK ABOUT GAMMA-RAY SOURCES

The research of deep space with gamma-rays has been developed as a novel discipline only in the recent three decades. After the discovery of X-rays from cosmic objects, first measurements of cosmic gamma-rays with the Apollo spacecraft confirmed expectations by theorists of violent processes occurring in the universe, which could be seen as gamma-ray sources. More detailed studies of theory and and new experiments in near-earth space instrumentation followed, and put this perspective on more solid grounds. Then NASA decided in the late 70's to devote a "Great Observatory" to an exploration of the gamma-ray sky. This became a great scientific achievment, with many new gamma-ray sources discovered and crucial details learned about known ones. After this mission was terminated in 2000, new deeper and complementing observations are being prepared, in this observational window with its unique information about high-energy physics in cosmic environments.

Here we elaborate on the underlying physical and astrophysical considerations of cosmic gamma-ray astronomy and the interpretation of its results. We do this by pursuing the questions:

- What are gamma-rays, compared to other radiation that we know of? What makes them so special that we need space observatories?

- What are the processes that make gamma-rays? How does a gamma-ray then interact with normal matter? How can we detect them?
- Which cosmic sites feature gamma-ray source processes? What do we learn by studying them?

Clearly we can not fully describe all details of these questions and their answers. But we will attempt to guide you into this area sufficiently deep so you can relate future lectures and articles on topics related to gamma-ray astronomy to the worlds of laboratory physics and of other astronomy branches.

WHAT ARE GAMMA-RAYS, COMPARED TO OTHER RADIATION THAT WE KNOW OF?

"Radiation" in common language often describes an effect which pervades our environment on straight paths with high penetration power; often exposure to radiation carries a conotation of "danger", be it "cosmic radiation", solar UV radiation, or mobile-phone radio waves. We know of two types of radiation: corpuscular and electromagnetic radiation. "Cosmic rays" as the example of the former are predominantly very energetic small particles pervading the Galaxy in the empty space between stars. "Electromagnetic radiation" on the other hand consists of propagating fluctuations in electrical and magnetic fields. Gamma-rays are electromagnetic radiation. The electromagnetic spectrum spans more than 20 decades of frequency, it ranges from the low-frequency / large wavelength regime of radio waves through the infrared, optical and ultraviolet regimes up to the high frequency / short wavelength regime of X and gamma-rays (see Figure 1). Wavelength and frequency are related through $c=\lambda\nu$ with c=speed

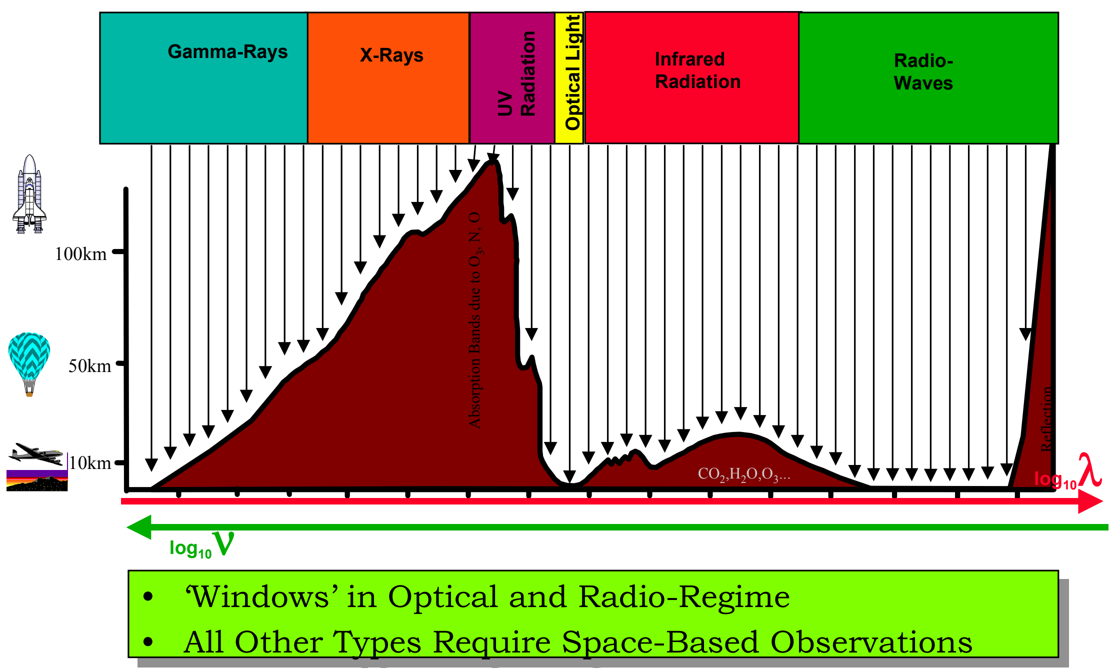


Fig 1: The spectrum of electromagnetic radiation, naming the different types of radiation from low-energy radio waves to high-energy gamma-rays. The vertical scale indicates how deep cosmic radiation will penetrate down through the Earth atmosphere to ground.

of light, measured as 300000 km per second, and λ being the radiation wavelength in km units, and ν the radiation frequency in cycles per second.

The subject gets more complicated in gamma-rays than it is at radio or optical wavelength because such energetic or „hard“ electromagnetic radiation shows effects similar to corpuscular radiation. This phenomenon is understood from the wave/particle dualism discovered early this century by de Broglie and others; it relates to the quantum nature of matter and electromagnetism, which nowadays even is studied in the area of gravity. Gamma-ray interactions with matter are less wave-like, and more particle-like. We can understand this from the following considerations:

When we study the interaction of material bodies with electromagnetic radiation, the relative dimensions of the two interacting partners play a leading role: For an electromagnetic wave, the characteristic dimension is its wavelength; for material bodies, it may be their geometrical size. Thin films of oil have thicknesses comparable to the wavelength of visible light, hence small variations in thickness of the oil layer strongly prefer reflection or absorption of light with correspondingly small wavelength differences, or slightly different colors. Therefore we can see nice colors of the oil film, caused by the differences in interference patterns of light waves of different wavelengths with this oil film. Now for X-rays or gamma-rays, the wavelength of the radiation is short compared to the spacing of the atoms in the material, hence the radiation mainly sees the atom's components, the compact nucleus and the electrons orbiting the nucleus far out, like planets orbit the sun. The atom thus mostly is "empty space" for an X or gamma-ray. An iteraction of a gamma-ray with matter will not occur as an ensemble of photons with the ensemble of matter, but rather in an individual and specific interaction with matter small-scale components, the electrons and nuclei. This resembles a collisional process, it becomes more appropriate to view X and gamma-rays as energetic particles, their characteristic size being their wavelength. So we can understand (see below) that materials which should act as mirrors for X and gamma-rays need very special geometries of their fundamental building blocks to operate at all, and will nevertheless cease to function below some critical wavelength. In such a particle picture, it becomes more appropriate to use the energy of the photon as its characteristic quantity, rather than its wavelength or frequency (reasons will become clear below, from the interaction of photons with matter and fields). Energy is measured in voltage units for electromagnetic particles (photons), one million electron volts (1 MeV) being the energy an electron would have if accelerated by a voltage of a million volts. The gamma-ray domain spans the energy regime above about 0.1 MeV, extending at least over five orders of magnitude in frequency / wavelength / energy. (For comparison, our eyes see the optical regime from about 0.4-0.7 micrometers in wavelength, from colors blue to red - a fairly modest dynamical range.)

WHAT MAKES GAMMA-RAYS SO SPECIAL THAT WE NEED SPACE OBSERVATORIES?

In spite of its penetrating power, there are limits to the range of gamma-ray photons in matter. In a thick layer of material you can imagine a gamma-ray must eventually hit an atomic nucleus in spite of their relatively large spacing, much like you would hit a tree when entering a forest on straight path in spite of a relatively large spacing between trees. The penetration depth for gamma-rays corresponds to a few grams of material per cm^2. Now how thick is the Earth's atmosphere in these terms (compare Figure 1)? For a characteristic atmosphere depth of 10 km, and a specific weight of air being one milligram per cm^3, this amounts to ~1000 g cm^{-2} - the Earth's atmosphere is a thick shield! This is good to protect us from cosmic radiation. But we must go to high altitudes above 40 km to be able to observe cosmic gamma-rays directly (remember: the stratification of the atmosphere is logarithmic, the density of the air falls off rapidly near earth, but more shallow at large altitudes; at 40 km, the residual atmosphere above still adds up to about 3 g cm^{-2}). Additionally, the irradiation of atmospheric gas by cosmic rays results in an enormously bright glow of the upper gas layers of the atmosphere in gamma-rays, much brighter than any cosmic sources. Instruments for observation of cosmic gamma-rays have to be lifted above this luminous layer with its maximum brightness at ~30 km altitude, and be sufficiently shielded to not confuse gamma-rays from the underlying atmosphere with cosmic gamma-rays.

How does this compare to other frequencies? Above description of the interaction between electromagnetic radiation and matter tells us that different effects will characterize the absorbing power of the atmosphere as we go up in frequency from radio waves to gamma rays. At radio waves (λ~1 m) the atmosphere does not present obstacles, the atoms are tiny compared to radio waves. When we go to shorter wavelengths and approach optical frequencies, different atom and molecule species have dimensions that resonate with radiation and hence absorb its energy -- the complex structure of the atmospheric absorption reflects the species characteristics: Molecules like water vapour absorb radiation in the infrared, atoms like oxygen and nitrogen strongly absorb radiation in the ultraviolet. A window remains in what we call the visible light -- this window determined the way how life was shaped on Earth. Further shortward, towards X rays, the inner electrons of atoms have characteristical orbital energies similar to the photon energies, and excitation of these electrons can absorb this radiation. Towards even more energetic radiation, the gamma-ray regime, scattering off electrons is the prime absorbing effect, with decreasing absorption power as the gamma-rays become more energetic. The different windows from the surface of the Earth into deep space (Figure 1) determine which kind of astronomy can be made from Earth: optical, radio, and upper-end gamma-ray measurements are possible from ground; spaceborn instrumentation is required for ultraviolet, X- and gamma-ray as well as infrared telescopes.

WHAT ARE THE PROCESSES THAT MAKE GAMMA-RAYS?

Electromagnetic radiation is distinguished among astrophysicists as either "thermal" radiation, or due to other special processes that are summarized as "non-thermal".

Thermal radiation is characterized by a temperature, and the spectrum of radiation intensity (or relative number of photons) versus frequency follows the "black-body" distribution. This distribution results from the population of the states of the radiation field, as derived by Max Planck and Ludwig Boltzmann early this century: the interaction of the radiating material and the radiation is so intense that the energy density of both are identical, equilibrium is obtained, and "temperature" is a unique and characteristic parameter. For increasing temperature, the black body distribution shifts its median towards more energetic radiation, so that each of the photons carries more energy, again balancing the increased energy of a hotter radiator. This shift is called Wien's law, the product of temperature and the wavelength of the peak of the radiation spectrum is a constant: 0.3 [cm K] = λ_{max} * T. From this relation, λ_{max} is in the visible regime for a temperature of 6000K, approximately the temperature of the sun's surface. The big bang residual radiation at 3K has its peak emission at radiation of millimeter wavelengths. Thermal gamma-rays of 1 MeV correspond to a temperature of above two billion degrees, a truly hot fireball! Note that nuclear fusion inside the sun occurs at 15 million degrees, so gamma-ray fireballs must be even much hotter. Clearly we cannot expect such energetic fireballs to withstand explosion. Therefore we expect to study violent explosions of fireballs through thermal gamma-rays.

The non-thermal processes to make gamma-rays are less extreme, being specific interaction processes of matter and radiation far from global energy equilibrium: We focus our attention to the exceptional processes that produce a gamma-ray photon, and do not require that the entire source environment obtains so much energy that the gamma-ray emission dominates all radiation processes.

Several processes are distinguished:

- Charged-particle acceleration in strong electric or magnetic fields:

  Moving charged particles, like electrons, can be seen as a current along a certain direction. The particle's charge polarizes the space around it, its motion thus translates into an electromagnetic field which varies as the charged particle moves. Any acceleration of the charged particle implies that the electromagnetic field

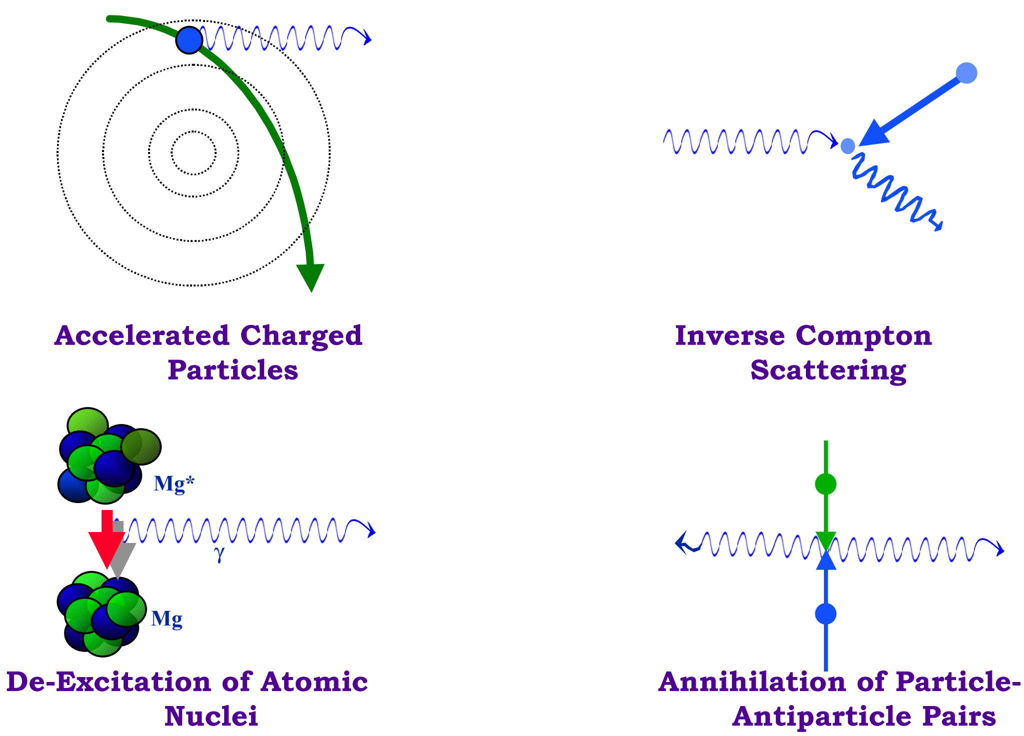


Fig 2: The types of physical processes which produce gamma-ray photons.

imprinted on space must be modified accordingly, there is no equilibrium configuration. This electromagnetic field rearrangement occurs at the expense of the charged particle's energy of motion, and we can understand that here kinetic energy is transformed into electromagnetic energy. At high interaction energies (i.e., around or above the particle's rest mass energy equivalents), the particle picture becomes more appropriate: Quanta of electromagnetic energy, the photons, are emitted by accelerated charged particles. From the process, these photons are called 'synchrotron' photons, and their distribution is markedly different from thermal photons. Energetic electrons (~1000 MeV) moving in the weak magnetic field of interstellar space within our Galaxy (field strength ~micro-Gauss) thus produce 'synchrotron' photons, which can be observed in the radio regime; stronger magnetic fields shift this radiation up in energy, into optical regimes for particle accelerators in high-energy physics laboratories, and into the gamma-ray regime near the surface of neutron stars. As a similar process, even the curvature of magnetic field lines in the vicinity of neutron stars can provide sufficient 'bending' acceleration to charged particles which move along those field lines, so that 'curvature radiation' is emitted, extending up to gamma-rays. In pulsars, we attribute part of the observable gamma-rays to this process. -- Another similar process occurs when a fast electron passes very closely by an atomic nucleus: the strong positive charge of the nucleus affects the electron's trajectory, and correspondingly 'bremsstrahlung radiation' is emitted in such an event, typically reaching into the gamma-ray regime for cosmic electrons. -- Summarizing: When the trajectory of energetic charged particles is significantly distorted by a strong field, emission of gamma-rays is a common result. Reversing this physical insight: The observation of gamma-rays may be used to study energetic particles moving in strong fields. ('Energetic' here means motion almost at the speed of light, 'strong fields' must be sufficient to substantially alter such energetic motion).

- Release of quanta of energy that fall into the gamma-ray regime:

  At microscopic dimensions, the quantum aspect of nature dictates that systems like atoms or nuclei cannot have any value of internal anergy -- rather, their possible energy states are 'quantized'. In systems with allowed energy states which are separated by MeV energies, the transition from a high energy state into a lower energy state will often proceed through emission of a single photon of that energy difference - a gamma-ray photon. Examples of such systems are:

  - Atomic nuclei: The nuclear (or strong) force holds together protons and neutrons in a compact structure called the atomic nucleus. The strong force outweighs the electric repulsion of all those positively charged protons at small distance, but the compact assembly of nucleons requires very specific, quantized, states of energy for the nucleons. The nuclear dimensions result in typical energy level spacings of ~MeV, hence any transition in states of atomic nuclei likely involves absorption or emission of MeV gamma-rays. Now we just need something which disturbs the state of a nucleus: An energetic collision at kinetic energies of MeV or more will just do that. This is the case when cosmic rays hit interstellar gas in our Galaxy. Another possibility for nuclear state disturbance is radioactive decay of an atomic nucleus. In such events, one of the particles of the nucleus transforms into one of another kind as a consequence of the 'weak force'; neutrons decay into protons ('β^--decay'), or protons can transform into neutrons ('β^+-decay'). This modifies the quantum state in this tight arrangement of nucleons, and new, stable arrangements have to be sought, through emission of the energy difference, often as a gamma-ray photon. Reversing this insight, the observation of characteristic gamma-ray lines thus tell us about nuclear transitions in a source region, hence about collisions or radioactivity.

- Decay of pions is a similar process. The pion ('Pi-meson') is an elementary particle which participates in the strong nuclear interaction, similar to protons or neutrons inside an atomic nucleus (we view pions as the carriers of strong interactions, in analogy to the photon carrying electromagnetic interactions). Pions are released during strong-interaction events like collisions of energetic protons with nuclei. Neutral pions decay preferentially into two gamma-ray photons, with an energy distribution which peaks at ~70 MeV, owing to the mass of the pion of ~135 in MeV units. Observation of a pion-decay peak in a gamma-ray spectrum thus testifies energetic collisions between protons, used in the study of cosmic proton accelerators.
- Pairs of particle and anti-particle: According to the equivalence of mass and energy discovered by Einstein early this century, energy may be converted into pairs of particle and anti-particle in the presence of a strong field. (Actually, one does not need an additional field for this conversion to occur, but the inverse process occurs so rapidly that there is no observable net particle production in the absence of fields). The lightest particle-antiparticle pair that can be generated is the electron and its antiparticle, the positron: it requires an avaliable energy of 1.022 MeV. The inverse process, when a particle encounters its anti-particle, is called 'annihilation': The mass of both particles is transformed into radiation-field energy. Momentum conservation demands that an electron-positron encounter will produce two photons, and each of those photons obtains an energy of 0.511 MeV in the rest mass system of the annihilation process. Annihilation photons thus are commonly produced in environments where anti-electrons are generated. These can be regions of high energy density and strong fields, as described above, but also radioactive decay processes involving 'beta-(β)-decays' from weak interaction: In a beta-decay, for example, a proton can decay into an anti-electron and a neutron (plus an electron-neutrino, we ignore this highly penetrating particle here). Annihilation photons of typical and well-defined energy 0.511 keV (a 'gamma-ray line') thus will tell us about radioactive-decay regions, and very violent regions of high energy density.
- Charged particles caught in strong magnetic fields: Similar to the electrical (or Coulomb) force which holds electrons close to a nucleus in the quantized system of an atom, strong magnetic fields can force electrons into orbits around their field lines. Magnetic fields close to neutron stars can be sufficiently strong such that the quantized energy levels involve steps between such allowed electron-orbit levels in the range of tens of keV, the 'low gamma-ray regime' (or 'hard X-ray regime'). Electron transitions from one allowed state

to another will generate or absorb photons of this characteristic step energy, resulting in 'cyclotron lines'.

- Up-scattering of low-energy photons through collisions with energetic particles: As we speak of light as 'particles', we can imagine thse to collide with other particles such as electrons. The collision, of a photon and an electron is called 'Compton scattering', and it is remeniscent of billard ball bounces. In 'normal' Compton scattering a gamma-ray photon will hit a (low-energy) electron within the atoms of some material, and be scattered by the collision, giving some of its energy to the electron. The inverse energetics may apply also, however, and result in a gamma-ray production process: If energetic electrons collide with photons of low energy, those photons often gain energy in such collisions, thus sre promoted in energy from X-rays to gamma-rays! This 'inverse Compton scattering' is important where high densities of photons (e.g. the starlight near the plane of our Galaxy), meet energetic electrons (like those in cosmic rays). Other inverse-Compton source examples may be compact stars, where the hot accretion disk shines in UV and X-rays, and the compact object generates beams of charged particles in the vicinity of this intense radiation.

Most of us are not familiar with these processes which produce gamma-rays; they even are not common in the universe, and go along with rather exotic conditions. In most cases, violent forces are at play. Observation of gamma-rays enables us to study such exceptional places in nature, which we cannot mimic in our laboratories on Earth.

HOW DOES A GAMMA-RAY INTERACT WITH OTHER MATTER?

From the above description of physical processes which involve gamma-rays, we can infer that gamma-rays do not interact with material surfaces (unlike optical light, which is deflected from mirror surfaces). Rather, the most common process is that gamma-rays scatter off electrons within materials, thus randomly penetrate some variable depth of material before their interaction; the scattering itself is a random process with a wide spectrum of possible directions and energies of the scattered photon, averaging out to

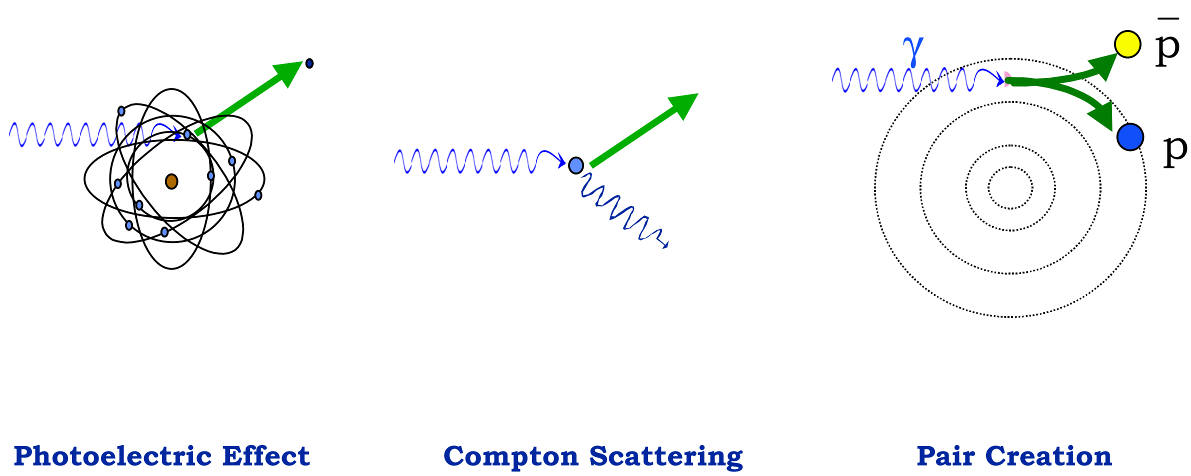


Fig. 3: Interaction processes of gamma-ray photons with matter

the distributions presented above when many interactions are summed. The fate of an Individual gamma-ray photon in material is not predictable.

The interaction processes vary with energy of the gamma-rays, and are (from low to high energy; see figure 3):

- Photoelectric absorption: atomic electrons are removed from their nuclei, thus removing the electron's binding energy from the gamma-ray photon. This is the dominant process at energies below ~ 100 keV.
- Compton scattering: electrons are hit by the gamma-ray photons, and obtain a fraction of the photon's kinetic energy in this collision. This is the dominating interaction process in the 0.1 MeV to a few MeV regime.
- Pair creation: In the electric field of the atomic nucleus, the gamma-ray energy is converted into a pair of electron and positron. In the rest frame of the gamma-ray, those two particles are generated with momenta into opposite directions; transformation into the laboratory coordinate system makes them appear as forking out of the gamma-ray's incidence direction with a small opening angle, which becomes smaller with increasing gamma-ray energy. This interaction process cannot occur below an energy of1.022 MeV, and increases upward in importance until it dominates over the Compton scatter process above several MeV. Ionization tracks from the charged particle pair can be usefully recorded well above ~10 MeV.

HOW CAN WE DETECT GAMMA-RAYS?

We can measure the effects of a gamma-ray interaction in special materials, by measuring the characteristics of secondaries after the interaction event: An electron obtains substantial energy through a Compton scattering interaction, then moving at high velocity through its surrounding material. Depending on the electron's energy, it may preferentially leave behind an ionization track, or excite 'light centers' in scintillating materials, or produce an electron-positron pair in the strong Coulomb field of an atomic nucleus. Obviously, we need to construct and optimize detectors which can measure with high precision the most likely outcome of a gamma-ray interaction. This immediately makes plausible that astronomical gamma-ray telescopes actually resemble high-energy physics laboratory equipment as we know it from terrestial particle-accelerator laboratories.

As an example, for the Compton Gamma-Ray Observatory of NASA, four different instruments have been constructed to measure gamma-rays. Each of these pursued a different strategy and optimization, such that complementary equipment covered the five decades of different gamma-ray energies (see Figure 4):

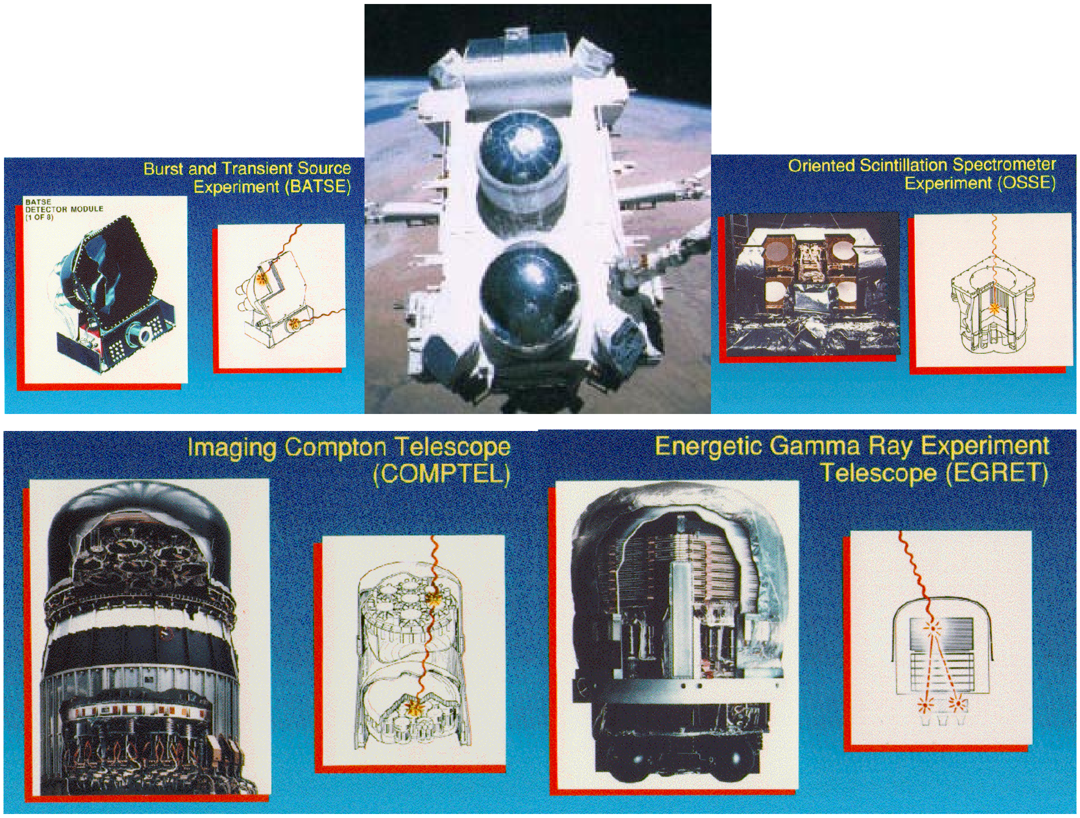


Fig 4: The Compton Observatory and its gamma-ray telescopes

The BATSE, OSSE, and COMPTEL telescopes feature scintillation detector units as their key elements. Optimized for different purposes and energy regimes, those detect the scintillation-light flashes which are left behind from fast electrons after cascades of Compton scatterings within those detectors. Glass blocks made of sodium-iodide are the basic material, impurities of thallium generate energy levels between the valence and conduction bands of the basic material; excited electrons cascading down through those levels produce scintillation light at colors that match the characteristics of the most sensitive light detectors available, the photo-multipliers. -- In the case of the imaging COMPTEL telescope, two layers of scintillation detectors of different kinds have been arranged to enable detection of a single Compton scatter of the incoming gamma-ray, through simultaneous detection of the Compton-scattered electron and its downward-scattered secondary photon. This multi-interaction coincidence technique reduces the efficiency for detection of gamma-rays. But if detected, valuable information about the incidence direction can be calculated from the measured quantities; this enabled us to image gamma-rays in this energy regime for the first time. -- The EGRET telescope is optimized for higher energy, where the generation of electron-positron pairs dominates the interaction of gamma-rays with matter. Incident gamma-rays produce pairs in the upper entry layer of the telescope, the main detector consists of a spark chamber detecting the ionzation tracks of those charged particles. The electron and positron have almost parallel trajectories, yet the weak magnetic field of the Earth bends their path sufficiently so that they do not annihilate with each other immediately. Back-projection of the electron and positron ionization tracks reveals the direction of the incoming gamma-ray, hence EGRET also is an imaging telescope. -- BATSE derives directional information from shadowing considerations, comparing gamma-ray intensities among their eight detectors at the extreme corners of the spacecraft. The short gamma-ray flashes in gamma-ray burst events ensure that these signals are well recognized against background gamma-ray emission. -- The OSSE scintillators have been equipped with collimators - sets of long tungsten pipes - which only allow gamma-rays to hit the scintillators from a narrow range of incidence directions; rocking the viewing angle of the collimator between two alternate directions enables the comparison of the gamma-ray brightness of such two directions in the sky, and thus the detection of cosmic point sources. – This set of telescopes has provided a complete exploration of the sky in gamma-rays, and led to the discovery of several new source object types, as well as to measurements of known sources at a precision sufficient for astrophysical model tests and interpretations. New instruments are under development for the next generation of gamma-ray astronomy. The ESA INTEGRAL mission emphasizes the hard-X and low-energy gamma-ray regime with its coded-mask telescopes. Imaging is achieved through casting a source shadow onto a position-sensitive detector array (Figure 5). An important new quality will be added by INTEGRAL through its largely-improved energy resolution, which will allow accurate line shape measurements for important gamma-ray lines from nucleosynthesis regions in particular. The NASA GLAST mission emphasizes the high-energy domain above ~100 MeV, where cosmic acceleration processes can be studied. A large particle-tracking telescope will improve the gamma-ray sensitivity over EGRET, and allow follow-up studies of gamma-ray pulsar details, gamma-ray jets from nuclei of active galaxies, and the diffuse gamma-ray emission from our Galaxy. Special missions which target gamma-ray bursts (HETE, SWIFT) also carry gamma-ray instrumentation of conventional types. As a next-generation advance, physicists develop new implementations of the most-promising Compton telescope design, with semiconductor layers as primary detectors, to achieve better background suppression and higher angular resolution (projects ACT, MEGA).

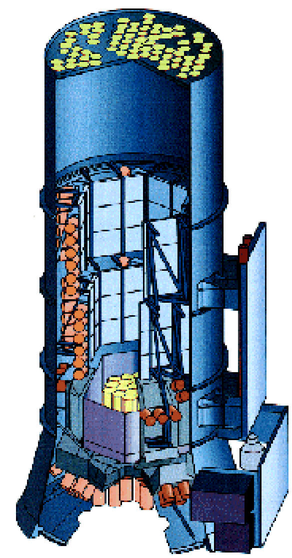


Fig 5: The SPI coded-mask imaging spectrometer on INTEGRAL

WHICH COSMIC SITES FEATURE GAMMA-RAY SOURCE PROCESSES?

Thermal radiation from a cosmic 'gamma-ray fireball' constitutes probably the most violent site one can imagine. Explosions of stars through supernovae in principle come close to this extreme. In those events, huge amounts of energy are released within short times (fractions of seconds), and thus may generate such extreme heat. For core collapse supernovae, the energy originates from the collapse of a star when nuclear burning in its core starved from fuel exhaustion, and no internal energy source can counterbalance the gravitational pressure of the overlying mass of the stellar gas. In the case of thermonuclear supernovae, accumulated nuclear fuel ignites on the surface of a perfectly heat-conducting compact remnant of a star (a 'white dwarf'), and causes the entire remnant to incinerate nuclear burning, consuming all the fuel in an instant due to the high compactness and heat conduction. Temperatures in those supernova conditions exceed several billion degrees, and cause atomic nuclei to melt and rearrange upon cooling down, with radioactivities as by products. Less extreme nuclear burning occurs in nova events, when the igniton of accumulated hydrogen fuel proceeds more slowly into a nuclear surface flame on the compact remnant. Temperatures in this case are below billion degrees, yet sufficient to generate radioactivities among the light elements which can undergo nuclear burning. The cores of these explosive events cannot be studied in gamma-rays however, because the hot inner regions of the event is hidden behind large amounts of overlying envelopes, thick enough to even occult gamma-rays. This occultation is the reason why the nuclear burning inside stars like our sun proceeds without associated gamma-ray luminosity of the star. For very massive stars 20 or more times as massive as the sun this is not necessarily so: Their atmosphere is more violently mixed, and strong stellar winds blow of large parts of the envelopes. Radioactive products generated in all those objects have in some cases sufficiently long decay times to produce their characteristic gamma-rays only after the explosion of the event or the stellar wind has sufficiently diluted the material. For radioactive-decay times which are long compared to the recurrence time of the ejection events, a picture of nucleosynthesis sources is obtained, which integrates over many such events and shows their distribution in space (see Figure 7). -- Direct gamma-ray observations of sufficiently hot fireballs may be possible for events where the energy release is not covered by stellar envelopes, such as neutron star collisions and similarly extreme and rare events, which have been discussed as the origins of gamma-ray bursts.

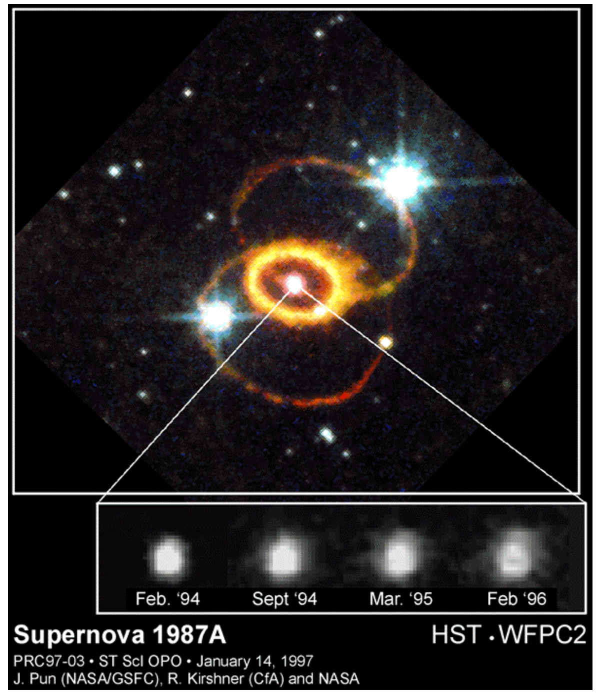


Fig 6: Supernova 1987A in the Large Magellanic Cloud galaxy ~150000 light years away: Picture of the explosion blast wave and its interaction with circumstellar material (producing the rings). (The white objects are foreground stars.) (Photo courtesy HST/ NASA)

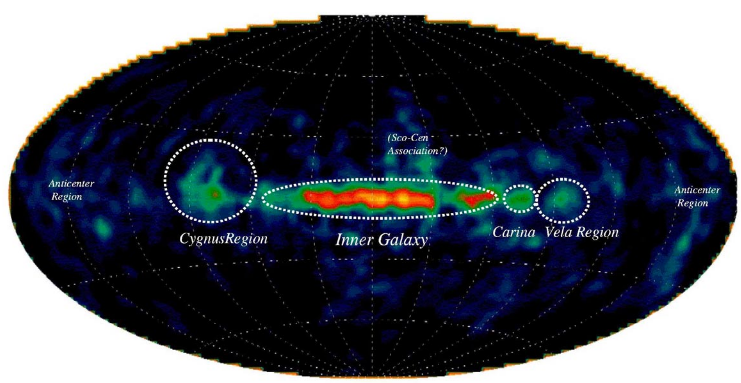
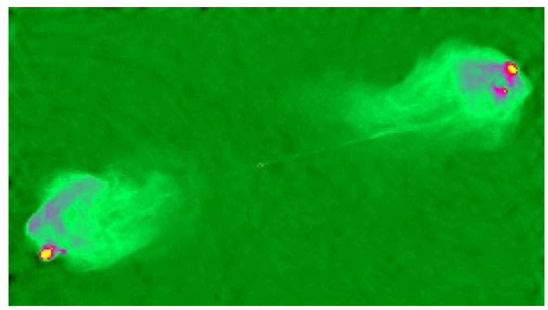


Fig 7: Radioactive glow of ^{26}Al along the plane of our Galaxy, as observed by the COMPTEL gamma-ray telescope

Non-thermal gamma-rays may provide unique insights to such processes, even though originating from secondary, non-equilibrium processes, like in the case of radioactive decay. The very compact neutron stars are known to be common sources of X-rays, mostly caused by release of gravitational energy when matter falls onto these 10 km-sized stars which are as massive as the sun. The complex path of matter when falling onto a neutron star in a strong gravitational and magnetic field is subject to a broad astrophysical study, involving radiation from radio frequencies to gamma-rays. The extreme plasma motions near the neutron stars is capable to generate complicated beams of particles, and these in turn produce the fascinating pulsing phenomena of these objects in the X-ray regime; close to the compact star, nuclear excitation of infalling matter from close to the neutron star's surface could be expected to result in characteristic line emission. Instrument sensitivities were inadequate so far to detect such nuclear lines from accreting neutron stars. - Further out in the magnetosphere, gamma-rays within a broad frequency range are known to be produced in isolated neutron stars whose magnetosphere is relatively undisturbed by accreting matter. The gamma-ray emission is attributed to curvature radiation of particles accelerated by large electrical fields. Observed pulsing behaviour varies strongly with frequency of the radiation, and can be explored to diagnose the plasma acceleration / magnetic field configurations in great detail. - their patterns are yet to be understood, with gamma-ray pulses observed only from half a dozen such objects due to the narrow beaming of this radiation. - On the other hand, charged particle accelerators of even bigger scales than the ones in neutron star magnetospheres are observed in the extremely luminous nuclei of a sub-type of galaxies, the 'active galactic nuclei' (Figure 8). Here the particle energies must reach the highest energies one can imagine from physics considerations, gamma-rays up to 10^{20}eV have been seen from one such object recently! Spectacular are the jets of plasma that are ejected from these active galaxies, extending many thousand lightyears into space. Most intense gamma-rays have been observed recently from such galaxies when our viewing angle directly peaks into such jets. We still have no idea what the source of this enormous energy could be, which makes these inner core of galaxies more luminous than thousand times the entire luminosity of the billions of stars of normal galaxies. It is possible that we can learn from detailed studies of nearby accreting compact stars how gravitational energy can be converted into jet-like plasma



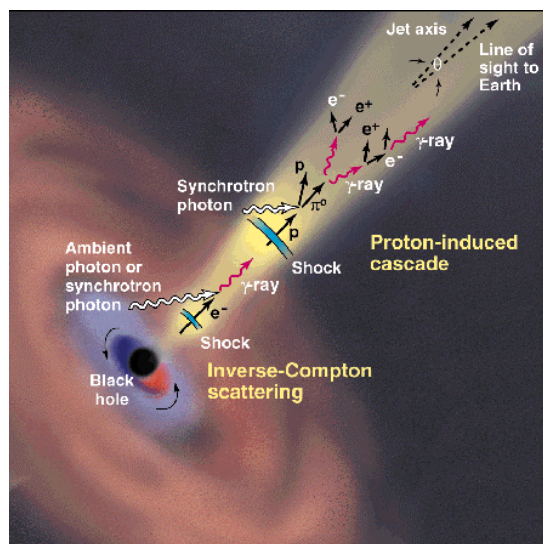


Fig 8: Nuclei of active galaxies, and the plasma jets: Radio emission from Cygnus A illustrates the huge dimensions of the plasma jet (above). Gamma-ray emission may arise from interactions of irregularities wthin the jet, or from jet interactions with ambient matter (below) (Pictures courtesy NRAO and GLAST)

beams, and if electrons or nuclei are the main carriers of energy under those conditions. On the other hand, magnetosphere physics near such objects reveals itself in studies of gamma-ray pulsars. Combining these lessons, gamma-rays can be unique tools to study the extremely violent active galaxies far out in the universe. We suspect that the combined gamma radiation from those active galactic nuclei comprises the major contribution to the general glow of the sky in gamma-rays, which has been termed the 'cosmic diffuse gamma-ray background'.

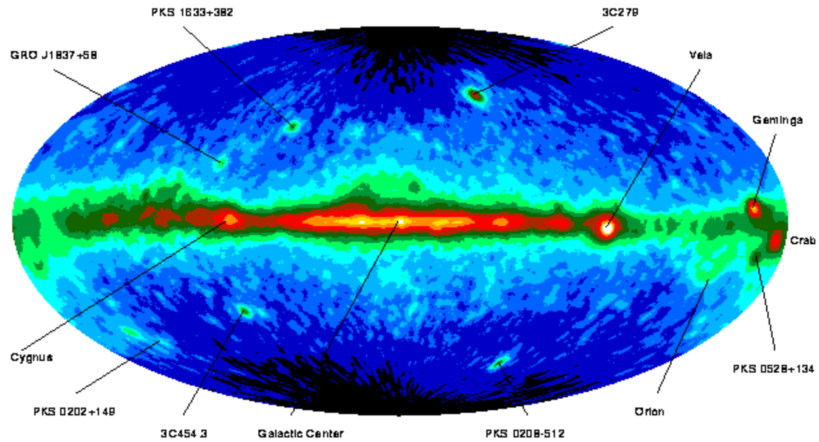


Fig 9: Diffuse glow of gamma-rays along the plane of our Galaxy, as observed by the EGRET gamma-ray telescope from interactions of cosmic radiation with interstellar gas. Gamma-ray bright active galaxies are indicated as well on this all-sky gamma-ray emission map. (Image courtesy EGRET collaboration)

The brightest gamma-ray emission observed from our Galaxy is caused by interaction of cosmic rays with interstellar gas (Figure 9). Predominantly bremsstrahlung processes cause a diffuse glow of the Galaxy in gamma-rays from MeV energies up to 10000 MeV, supplemented by pion decay contributions and inverse Compton gamma-rays from starlight which is boosted by cosmic rays to gamma-ray energies. This gamma-ray glow provides our unique trace to study cosmic rays indirectly throughout the Galaxy. The sources of cosmic rays, the bath of charged particles with energies up to 10^{20} eV, are still unknown. Acceleration by the violently expanding remnants of supernova explosions is one of the explanations that have been proposed, and seems plausible up to 10^{15} eV; at higher energies, the acceleration processes in nuclei of active galaxies are the best candidate explanation.

THE GAMMA-RAYS' FATE ON THEIR WAY FROM SOURCE TO ASTRONOMICAL IMAGE

On their journey from their cosmic sources to our detectors, gamma-rays may traverse regions with high chances for some kind of interaction; particularly risky regions are near the sources because of their often extreme density in matter and/or energy, and also in the vicinity of our bulky telescope equipment within the solar system in near-Earth space. In both regions we will obtain undesired side effects to our measurement, and we must account for them in our astronomical studies.

In dense environments, gamma-rays will scatter off electrons mostly, and loose part of their energy to the plasma. Such Compton scattering will therefore modify the shape of the spectrum of gamma-rays, and we must account for the plasma conditions in order to deconvolve the original source gamma-ray spectrum. Note that photons may also *gain* energy in such plasma collisions, if the plasma is more energetic than the photons.

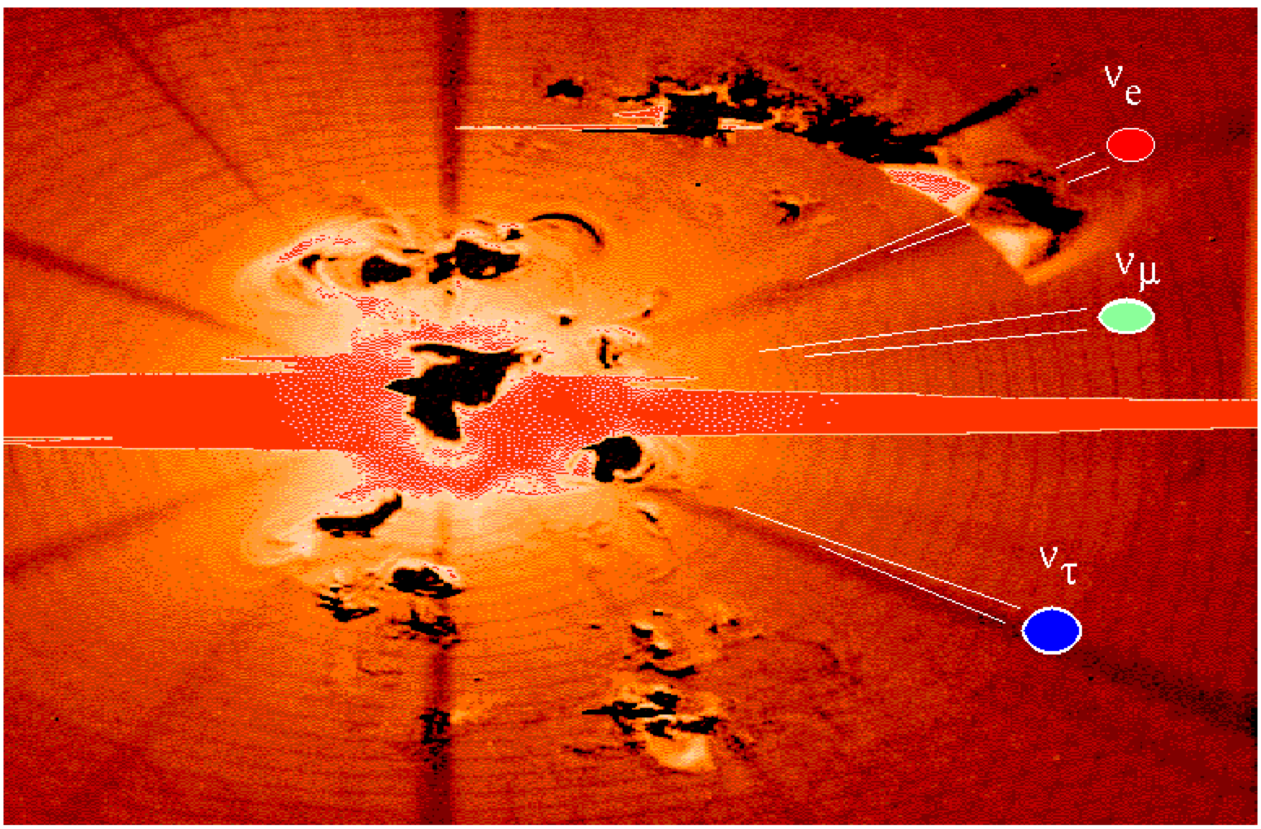
On the other hand, the profile of a measured gamma-ray line will also tell us directly about the relative motion of the gamma-ray source and our observing telescope: Doppler shift of the original frequency modifies the energy of gamma-rays, and frequency shifts down to ~100 km sec^{-1} can be measured; typical stellar relative motions are slower, but stellar wind velocities rise up to 1000 km sec^{-1}, and in explosions gas velocities beyond 10000 km sec^{-1} are obtained. Thus, e.g. the expanding motion of radioactive matter after a supernova explosion is expected to display a line width of ~0.1 MeV for a 1 MeV line energy, while in our laboratory, this line would be narrower than typical instrumental resolutions of ~ 0.001 MeV. Note that the gravitational field of compact sources such as neutron star surfaces can also result in substantial shifts of line energies: photons have a hard time to leave the star against this strong gravity, and can loose ~ 20% of their energy, with a corresponding lowering of photon frequency.

On their way after having left the source region and its environment, gamma-rays traverse long ranges of interstellar space without distortion: Although interstellar space absorbs optical radiation readily through its gas and dust at equivalent column densities of 10^{23} hydrogen-atoms cm^{-2}, such a material thickness amounts to less than 0.1 g cm^{-2}, practically transparent to gamma-rays (such effective material thickness corresponds roughly to a sheet of paper: optically, we cannot look through easily, but gamma-rays hardly notice this material).

Close to the detector, gamma-rays encounter the gas of the upper atmosphere of the Earth, plus material from a massive spacecraft carrying our telescope. Scattering and absorption are particularly important for telescopes on stratospheric balloons, and on large space observatory platforms often telescopes have severe limitations in their free and unocculted views of space from spacecraft structure or neighboring instruments. The enormous bombardement of the spacecraft by charged particles from the radiation belts and from cosmic radiation, results in a glow of gamma-rays from spacecraft and instrument, similarly the Earth atmosphere shines bright in gamma-rays. Our telescopes have been built with complex triggering and measurement equipment to discriminate the cosmic primary gamma-rays from this background. Powerful analysis algorithms then are employed to pull out an image of the gamma-ray sky from such complex raw measurements.

WHAT DO WE LEARN BY STUDYING GAMMA-RAY SOURCES?

The cosmic objects which can be studied best by gamma-rays clearly comprise the most violent and energetic sites within our universe. Theories of *nucleosynthesis* can be tested with observations of radioactivity gamma-rays; the COMPTEL ^{26}Al mapping of the entire sky is a textbook example. Gamma-ray astronomy attempts to get access to astrophysical pocesses directly through observations of gamma-ray lines, following the example of optical astronomy: the relation of a line to a unique type of object allows more specific interpretations. Study of *accelerated cosmic plasma*, electrons and protons at energies and densities much above what can be achieved in terrestial laboratories can be done with gamma-rays in a variety of sites: *cosmic rays and their origin* is studied through diffuse Galactic gamma-rays, *neutron star magnetospheres* with the pulsar phenomenon are our nearby cosmic laboratory, only thousands of lightyears away, while the plasma jets from *active nuclei in peculiar galaxies* at distances of millions of light years certainly illustrate the large-scale extreme. In between, *acceleration of cosmic rays* throughout our Galaxy is expected to leave trace gamma-rays, both with continuous energy spectra over the full range of the Compton observatory instruments, as well as through nuclear excitation lines in the MeV region. *Matter accretion onto compact objects* such as neutron stars and black holes is expected to release sufficient gravitational energy to power gamma-ray source processes of different kinds -- binary systems in our Galaxy may share physical processes with active nuclei of galaxies, only at different scales. And finally, the phenomenon of *gamma-ray bursts*, where one source in the sky outshines the rest of the universe for seconds to minutes, is still mysterious in spite of more than ten years of intense study and the spectacular advances in afterglow detections and analyses - most likely again extremely violent processes related to gravitational collapse of one or two stars may be at the origin of this phenomenon.



Roland Diehl, Garching/Germany, March 2001