γ-Ray Emission Processes

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References:

Diehl, R. 2000, "Gamma-Ray Production and Absorption Processes," preprint,

`http://astro.estec.esa.nl/SA-general/Projects/Integral/integ_objenum.html#astronomy`

Murthy and Wolfendale 1993, *Gamma-Ray Astronomy*, 2nd ed. (Cambridge)

1. Continuous processes
   (a) Black-body radiation
   (b) Particles accelerated in/by strong fields
   (c) Inverse Compton scattering
2. Discrete processes
   (a) Nuclear transitions
   (b) Decays of unstable particles
   (c) Annihilation

Reminder: $\lambda \lesssim 0.1$ Å, $E \gtrsim$ 100 keV

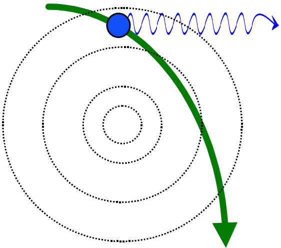
Black-body radiation

Temperature for which peak of black-body I_λ spectrum is $\lambda = 10^{-3}$ Å: more than 2×10^9 K.

Reached in:

- Interiors of evolved stars
- Explosion fireballs (supernovae)
- Big Bang at early times

Therefore, nonthermal processes (mean energy of particles not characterized by ambient temperature) more likely sources of γ-rays.



Accelerated Charged Particles

Charged particles in strong fields

Electric fields: bremsstrahlung

In electron-ion collision:

- $I_\nu(E_e) \propto (nZ^2/v_e)$ roughly with n the electron density
- All emitted photon energies equally probable up to electron K.E.
- Distinguish between thermal and nonthermal according to energy distribution of electrons and ions

- Nonthermal: power-law spectra like

$$dN_e/dE \sim E^{-\alpha}$$

  with $\alpha \sim 1 - 3$.

- Usually, electron-ion bremsstrahlung encountered at low energies. But, in the γ-ray energy regime, electron-electron bremsstrahlung is competitive.

Magnetic fields

Particle gyrates around field line at pitch angle θ.
Peak of synchrotron spectrum is

$$\nu_c \propto \gamma^2 B / \sin\theta$$

.

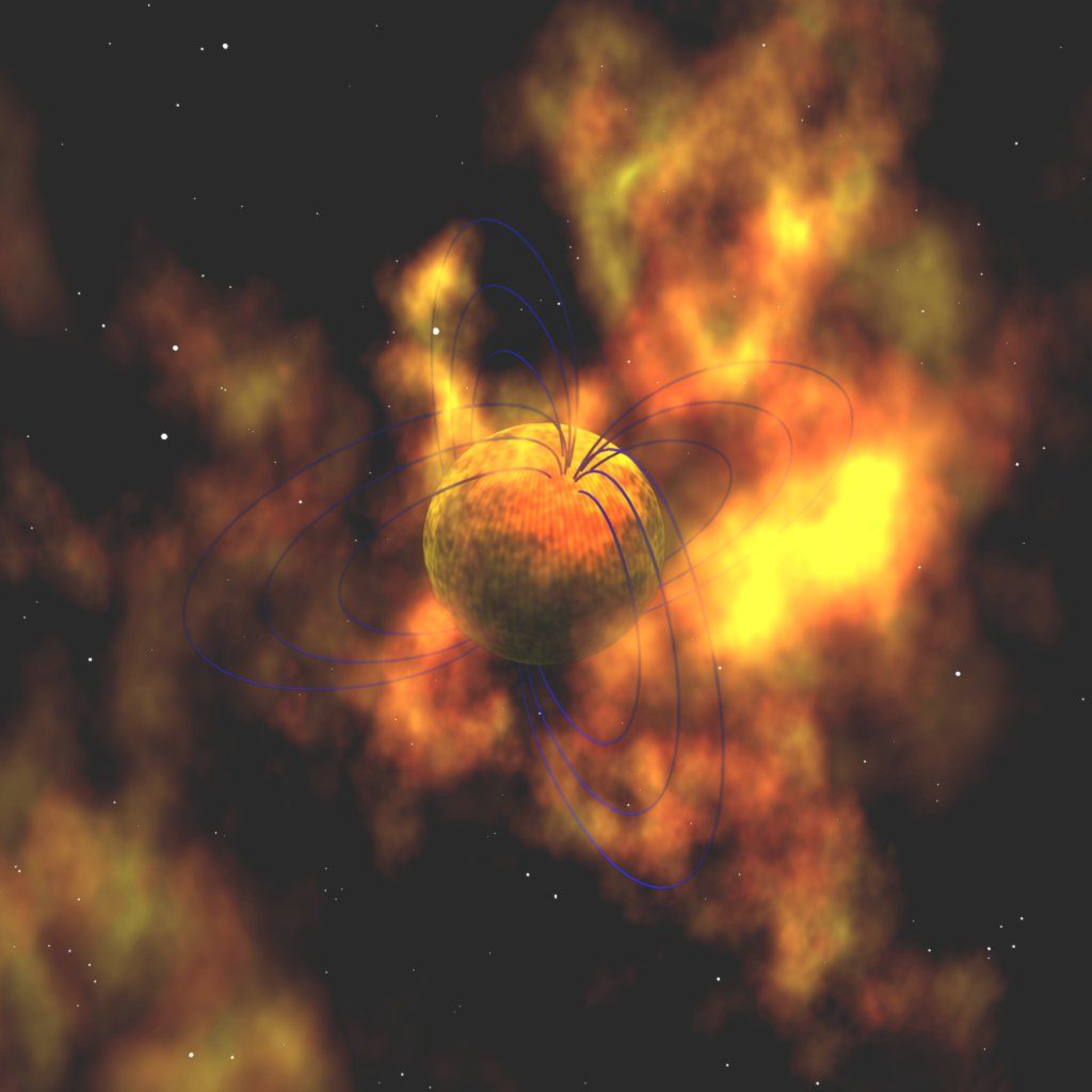
Production of γ-rays requires fields of order found near neutron stars.

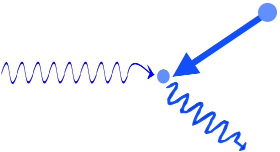
With field $\geq 10^{10}$ G, particle traveling along field line without gyration will produce ‘curvature radiation.’

In even stronger fields ($\sim 10^{13}$ G), more complex behavior:

- Relativistic effects
- Pair creation
- Multi-photon states (quantum phenomenon)

See magnetars.





Inverse Compton Scattering

Inverse Compton scattering

Important when photon density is high.

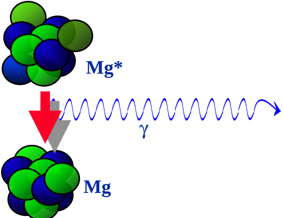
Well-defined spectral energy distribution for monochromatic incident photons, single particle energy

Energy of scattered photons rises steeply with energy:

$$E_\gamma \propto {E_e}^2 E_{ph}$$

where E_{ph} is the typical energy of the ambient photon field.

Therefore, the process is important in γ-ray sources.



De-Excitation of Atomic Nuclei

Nuclear transitions

Bound quantum systems, nuclei have discrete energy levels with spacings ~ 1 Mev.

Some important first-excited states

- $^{12}C^*$, 4.44 Mev
- $^{16}O^*$, 6.13 Mev
- $^{26}Mg^*$, 1.81 Mev

Processes that may leave nuclei in excited (disordered) states:

- Collisions of MeV cosmic rays on interstellar gas targets (cross section largest in resonances)
- Radioactive decay, especially weak decays.

$$n \rightarrow p + \beta^- + \bar{\nu}_e$$

$$p \rightarrow n + \beta^+ + \nu_e$$

  Radioactive parents made in regions of active nucleosynthesis.

Thus, γ-ray astronomy probes regions of nucleosynthesis and regions of enhanced cosmic-ray activity.

Supernova remnants are a good example of both.

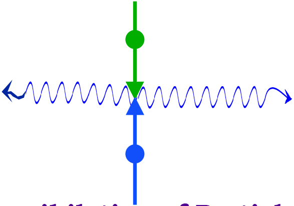
Pion decay

Somewhat similar to above nuclear processes.

Pions, rest mass $\simeq 140$ MeV, are created in strong-interaction processes such as collisions of cosmic rays on ambient nuclei.

$$\pi^0 \rightarrow \gamma + \gamma$$

with energy spectrum of γ-rays peaking at about 70 MeV, broadened according to momentum distribution of colliding particles.



Annihilation of Particle-Antiparticle Pairs

Particle-antiparticle annihilation

Pair production in strong EM fields, which cause particles produced by fluctuations in vacuum to drift apart before they can be annihilated again.

In collision between particle and antiparticle, spin and momentum conservation results in two photons.

Because of conservation laws, positronium in triplet state produces 3 photons sharing total rest energy of 1.022 MeV.

γ-ray spectrum has maximum energy of 0.511 MeV and continuous tail toward lower energy.

Likely environments

- Radioactive decay regions (cosmic rays, nucleosynthesis)
- Surface, near vicinity of neutron stars, black holes

Charged particles confined in strong magnetic field

Particle in a box, quantized Landau energy levels
$E = h\nu_c$,

$$\nu_c = ZeB/2\pi\gamma m_0$$

With $B \sim 10^{12}$ G as in strongly magnetized neutron stars, cyclotron lines are in X-ray regime,
$h\nu \sim 10$ keV.

Absorption and loss processes

Scattering on electrons within materials, generally incoherent (no diffraction pattern)

Processes, from low to high energy

- Photoelectric absorption: removal of inner-shell electron from an atom. Energy of γ-ray is reduced. ($< 100keV$)
- Compton scattering (0.1 MeV to a few MeV)
- Pair creation in presence of electric field (usually atomic nucleus). Dominates over Compton scattering above a few MeV.

- Absorption in upward transition among Landau levels; other absorptions by ions trapped in strong magnetic fields.

Interesting environments

Fireballs (gamma-ray bursts, maybe near black holes)

Explosions of extreme energy density (novae, supernovae)

Energetic collisions: accreting compact objects, microquasars, AGN, solar flares

Strong gravitational or magnetic fields leading to charged-particle beams: quasars, AGN