Observing the X- and Gamma-Ray Sky
Diffuse emission

J. Knödlseder
Centre d’Etude Spatiale des Rayonnements
Toulouse (France)
Lecture Outline

I. What is diffuse emission?

II. Diffuse emission processes

III. The X- and Gamma-Ray Sky
   • Sky images
   • The galactic emission spectrum

IV. The nature of galactic X- and Gamma-Ray emissions
   • The Galactic Ridge X-ray emission (GRXE)
   • The hard X-ray Sky
   • Positron annihilation
     (imaging diffuse emission)
   • Galactic Radioactivities
   • The MeV - GeV Sky
   • The TeV Sky

V. Summary & Bibliography
Diffuse or not diffuse - that is the question

Allsky image in visible light (Mellinger 2000)
A working definition for diffuse emission

**Dictionary:**
Diffuse = widely spread; not localized or confined; with no distinct margin

**Astronomer:**
“all emission that I cannot resolve into individual (point-) sources”
- depends on instrument characteristics (angular resolution, sensitivity)
- is not of much help for an astrophysicist

**Astrophysicist:**
“all emission processes that are related to interstellar (-planetary, -galactic) matter”
- emission of gas and dust (thermal, non-thermal)
- emission related to magnetic fields (synchrotron)
- emission related to diffuse stellar ejecta (particle diffusion)
- also applicable to extragalactic diffuse (e.g., intergalactic matter in clusters)
- also applicable for cosmic backgrounds (e.g., primordial matter for CMB)
Diffuse emission processes

**Continuum emission**

Interaction of high-energy CR *electrons* and *nucleons* with gas and radiation in the ISM:

- **Inverse Compton electron scattering**
- **Bremsstrahlung**
- **Pion ($\pi^0$) production and decay**
  \[ p + p \rightarrow p + p + \pi^0 \rightarrow 2\gamma \]
  \[ E_p > 300 \text{ MeV} \]

**Line emission**

Excitation of *electrons* and *nucleons* in an atom; antimatter *annihilation*:

- **Ionic lines** (below 10 keV)
- **Nuclear radioactive decay**
- **Nuclear excitation**
- **Positron-electron *annihilation* (511 keV line)**
A high-energy gallery of the sky

keV

TeV
The Soft X-Ray Sky (1 - 3 keV)
The X-Ray Sky (2 - 20 keV)

HEAO-1
The Hard X-Ray Sky (25 - 50 keV)

SPI / INTEGRAL (2 yr)
The Hard X-Ray Sky (50 - 100 keV)

SPI / INTEGRAL (2 yr)
The Hard X-Ray Sky (100 - 200 keV)

SPI / INTEGRAL (2 yr)
The Hard X-Ray Sky (200 - 300 keV)
SPI / INTEGRAL (2 yr)
The Gamma-Ray Sky (300 - 400 keV)

SPI / INTEGRAL (2 yr)
The Gamma-Ray Sky (400 - 500 keV)

SPI / INTEGRAL (2 yr)
The Gamma-Ray Sky (511 keV line)

SPI / INTEGRAL (2 yr)
The Gamma-Ray Sky (514 - 1000 keV)

SPI / INTEGRAL (2 yr)
The Gamma-Ray Sky (1 - 3 MeV)

COMPTEL / CGRO (6 yr)
The Gamma-Ray Sky (1809 keV line)

COMPTEL / CGRO (9 yr)
The Gamma-Ray Sky (3 - 10 MeV)

COMPTEL / CGRO (6 yr)
The Gamma-Ray Sky (10 - 30 MeV)

COMPTEL / CGRO (6 yr)
The HE Gamma-Ray Sky (30 - 100 MeV)

EGRET / CGRO (4 yr)
The HE Gamma-Ray Sky (100 - 300 MeV)

EGRET / CGRO (4 yr)
The HE Gamma-Ray Sky (300 - 1000 MeV)
EGRET / CGRO (4 yr)
The HE Gamma-Ray Sky (1 - 30 GeV)

EGRET / CGRO (4 yr)
The VHE Gamma-Ray Sky (0.1 - 20 TeV)

H.E.S.S.
The galactic diffuse emission spectrum

- $10^{38}$ erg s$^{-1}$
- 511 keV (e$^+e^-$)
- SPI (incl. sources)
- 1808.65 keV ($^{26}$Al)
- 1 GeV
- 1 TeV

Energy Flux (MeV cm$^{-2}$ s$^{-1}$ rad$^{-1}$)

Photon Energy
X-ray galactic ridge emission

EXOSAT 2-6 keV map (Warwick et al. 1985)

X-ray (2-10 keV) emission components
- point sources (X-ray binaries)
- unresolved (or diffuse) emission

Galactic ridge X-ray emission (GRXE)
- exponential disk & bulge components
- confined to the inner disk (|l| < 60°)
- disk scale height $z_0 \sim 100 - 300$ pc
- luminosity $\sim 10^{38}$ erg s$^{-1}$ (2 - 10 keV)
  (few % of resolved sources luminosity)

Origin of GRXE
- unresolved point sources?
- truly diffuse emission?
Deep X-ray surveys (XMM & Chandra)

- XMM & Chandra detect new faint point sources and prominent diffuse emission
- Only 10-20% of flux originates from point sources, 80-90% of the emission is diffuse
- Soft (< 2 keV) point sources are of galactic origin
- Hard (2-10 keV) point sources are of extragalactic origin
- Prominent emission lines from highly ionized heavy elements
Point-source origin

(Ebisawa et al. 2005)

(Koyama et al. 1986)

Point source hypothesis
- Candidate must have a thin thermal plasma spectrum with iron line emission
- Candidate population requires rapid steepening of log N-log S at low flux (<3 x 10^{-15} erg s^{-1} cm^{-2})

Candidates
- NS binaries (10^{36-38} erg s^{-1}): rarely show iron line, most of them are individually resolved
- RS CVn / CVs (10^{30-32} erg s^{-1}): resolved by Chandra/XMM, but not numerous enough
- Low luminosity population (<10^{30} erg s^{-1}): >10^9 sources required within Galaxy
Diffuse origin

Inverse Compton scattering of microwave background, FIR photons, starlight
- fall short by 2 orders of magnitudes
- CR scale-height of > 1 kpc does not match the GRXE scale-height

Synchrotron radiation
- requires $\sim 10^{14}$ eV electrons $\Rightarrow$ unclear whether they exist (solar modulation)
- large energy input required to sustain electron population $\Rightarrow$ ionisation of ISM

Thermal equilibrium plasma
- requires $T \sim 10^7 - 10^8$ K $\Rightarrow$ plasma exceeds escape velocity from galactic plane
- requires $P/k \sim 10^5$ cm$^{-3}$ K $\Rightarrow$ exceeds pressure of other ISM components
- required energy density $\sim 10$ eV cm$^{-3}$ $\Rightarrow$ 1-2 orders of magnitudes higher than CR, B, n

CR interactions with interstellar medium
- interactions of low-energy CR $e^-$, in-situ accelerated $e^-$, or heavy ions with ISM
- hard X-ray emitting SNR AX J1843.8-0352: possible link between GRXE and SNRs
Finally point sources?

**RXTE/PCA 3-20 keV image (Revnivtsev et al. 2006)**

**Morphology**
- tri-axial bar/bulge & exponential disk
- distribution very similar to NIR (e.g., COBE 3.5 µm)
- bar tilt angle: $29^\circ \pm 6^\circ$ (COBE NIR data: $20^\circ \pm 10^\circ$)
- exponential tilt angle: $z = 130 \pm 20$ pc
- position of Sun above gal. Plane: $z_0 = 20 \pm 7$ pc

**Luminosities**
- $L_{X,\text{bulge}} = (3.9 \pm 0.5) \times 10^{37}$ erg s$^{-1}$
- $M_{\text{bulge}} = (1.0 - 1.3) \times 10^{10} M_\odot$
- $L_X/M_\odot = (3.5 \pm 0.5) \times 10^{27}$ erg s$^{-1}$
- Comparable with cumulative emissivity per unit stellar mass of point X-ray sources in solar neighbourhood (coronally active late-type binaires and CVs)
INTEGRAL resolves the hard X-ray ridge

RXTE & OSSE (Valinia & Tatischeff 2001)

IBIS (Lebrun et al. 2004)

Hard X-ray emission components
- < 10 keV
  RS (= GXRE)
- 10 - 200 keV
  PL (exponentially cut-off powerlaw)
- > 200 keV
  HE (high-energy flattening)

PL (exponentially cut-off powerlaw)
- IBIS detects many point source towards the galactic bulge region
- Most of the total emission is attributed to point sources
  20 - 40 keV: 87% attributed to point sources
- By combining IBIS (point sources) and SPI (total emission)
  100 - 200 keV: 86% attributed to point sources
The hard X-ray to soft $\gamma$-ray transition

OSSE spectra (Kinzer et al. 1999)

Emission components
- < 200 keV (hard X-rays)
  PL (exponentially cut-off powerlaw)
- 200 - 511 keV (soft $\gamma$-rays)
  Pscont (Positronium continuum, towards bulge only)
- > 511 keV ($\gamma$-rays)
  HE (high-energy power-law tail)

Is the transition hard X-ray $\Rightarrow$ soft $\gamma$-ray a point source $\Rightarrow$ diffuse emission transition?
Antimatter annihilation in the Milky-Way

• Direct annihilation

• Annihilation via positronium (Ps) formation

para-positronium 1/4

ortho-positronium 3/4

Annihilation line
E = 511 keV

Positronium continuum
E < 511 keV
Positron annihilation: spatial distribution

Observations

- No point sources seen (SPI & IBIS)
- Continuum and line are spatially consistent
- Galactic bulge dominates emission
- Only small signal from galactic disk (~3σ)
- B/D luminosity ~ 3 - 9

Implications

- Positron annihilation distribution is unique
  Once we identify the source we certainly learn something new! (new population, new mechanism, new physics, ...)
- Weak galactic disk signal compatible with $^{26}$Al decay
Indirect imaging: deconvolving SPI data

Iteration 1

Exposure

Flux

Log likelihood

Alsky flux (ph cm$^{-2}$ s$^{-1}$)

Log likelihood-ratio

Iteration
Indirect imaging: deconvolving SPI data

Iteration 5

Exposure

Flux

Log likelihood
Indirect imaging: deconvolving SPI data

Iteration 10

Exposure

Flux

Log likelihood
Indirect imaging: deconvolving SPI data

Iteration 17

Exposure

Flux

Log likelihood
Indirect imaging: deconvolving SPI data

Iteration 25

Exposure

Flux

Log likelihood
Indirect imaging: deconvolving SPI data

Iteration 40

Exposure

Flux

Log likelihood
Indirect imaging: deconvolving SPI data

Iteration 70

Exposure

Flux

Log likelihood
Indirect imaging: deconvolving SPI data

Iteration 100

Exposure

Flux

Log likelihood
Suppressing noise

Richardson-Lucy (iteration 17)

MREM (Knödlseder et al. 1999)

Model fitting (bulge + old disk)

Model fitting (halo + old disk)
**Positron annihilation: spatial distribution**

![SPI Pscont image (Weidenspointner et al. 2006)](image1)

![SPI 511 keV image (Knödlseder et al. 2005)](image2)

**Observations**
- No point sources seen (SPI & IBIS)
- Continuum and line are spatially consistent
- Galactic bulge dominates emission
- Only small signal from galactic disk (~3σ)
- B/D luminosity ~ 3 - 9

**Implications**
- Positron annihilation distribution is unique
  - Once we identify the source we certainly learn something new! (new population, new mechanism, new physics, ...)
- Weak galactic disk signal compatible with $^{26}$Al decay
Positron annihilation: spectral distribution

SPI spectral fitting
- Energy $510.98 \pm 0.03$ keV
- $\text{FWHM}_n$ $1.3 \pm 0.4$ keV
- $\text{FWHM}_b$ $5.4 \pm 1.2$ keV
- $\text{Flux}_n$ $7.2 \times 10^{-4}$ ph cm$^{-2}$ s$^{-1}$
- $\text{Flux}_b$ $3.5 \times 10^{-4}$ ph cm$^{-2}$ s$^{-1}$

Interpretation
- Narrow line ($1.1$ keV)
  - thermalised positrons
  - consistent with $8000$ K warm ISM (neutral & ionised)
- Broad line ($5.1$ keV)
  - inflight positronium formation
  - consistent with $8000$ K warm ISM (only neutral, quenched if gas is fully ionised)
- Narrow / broad line fraction $\sim 2$
  - consistent with $8000$ K warm ISM (50% ionised)
Radioactive decay in the Milky-Way

**Distribution of $^{26}$Al and $^{60}$Fe in the ISM**
- velocity of 1 km/s corresponds to a distance of 1 pc with 1 Myr
- SN ejection velocities: 1000 - 10000 km s$^{-1}$ (but slow down)
- WR wind velocities: several 1000 km s$^{-1}$
- SN or wind blown bubbles: 10 - 100 pc
- $^{26}$Al and $^{60}$Fe should lead to diffuse emission, nuclei probably thermalised
- Short livetime isotopes ($<100$ yr, such as $^{44}$Ti, $^{7}$Be, $^{22}$Na, $^{56,57}$Co): point-like emission ($<$pc)
$^{26}$Al decay 1809 keV line emission

1809 keV line: radioactive $^{26}$Al production
- H and C-burning nucleosynthesis
- Hydrodynamic and explosive
- Stellar wind ejection (O, LBV, WR)
- Supernovae ejection (type II, Ib/c)
- Probe stellar mixing processes
- Traces massive stars

$^{26}$Al production and massive stars
- 1809 keV emission correlates to microwave free-free emission
- Free-free: ionised ISM (O stars, $M>20\, M_\odot$)
- $Y_{26} = 10^{-4}\, M_\odot /O7V$

COMPTEL image (Knödlseder et al. 1999)

DMR microwave image (Bennett et al. 1992)
Calibrating stellar models

Understanding $^{26}$Al nucleosynthesis in Cygnus

- Bright 1809 keV line feature
- Massive star population of Cygnus region is known (IR surveys)
- Estimate expected 1809 keV line flux using nucleosynthesis models and stellar population models (Cerviño et al. 2000; Knödlseder et al. 2002)
- Validate model using multi-wavelength properties (e.g. ionizing flux)
- 1809 keV flux underestimated by at least a factor of 2 (mixing?, stellar rotation?)

1809 keV $\gamma$-rays (COMPTEL)  Infrared (IRAS)  Radio (DRAO)
1809 keV line emission traces galactic rotation

26Al kinematics
- Galactic rotation (v ~ 200 km s⁻¹) leads to Dopplers shifts (~ 1 keV)
- Expected average line shifts ± 0.3 keV (from CO)
- Measured line shifts ± 0.3 keV (SPI/INTEGRAL)
- Confirmation of galaxy-wide $^{26}$Al production ($2.8 \pm 0.8 \, M_\odot$)
- Using yield estimates (theory) this converts into SFR of $4 \, M_\odot \, yr^{-1}$

INTEGRAL spectra (Diehl et al. 2006)
$^{60}$Fe: A long way to a faint radioactivity

**SPI/INTEGRAL and RHESSI measurements**
- $^{60}$Fe / $^{26}$Al flux ratio $\sim 10\%$
- $^{60}$Fe / $^{26}$Al abundance ratio $\sim 0.23$

**Interpretation**
- $^{60}$Fe only produced in core-collapse evens
- $^{26}$Al produced in core-collapse and WR winds
- Expected core-collapse $^{60}$Fe / $^{26}$Al ratio too large
- WR winds contribute significantly to galactic $^{26}$Al nucleosynthesis
Diffuse MeV and GeV Gamma-Ray emission

Point sources
- Pulsars
- Supernova remnants
- AGN (extragalactic)
- unidentified sources

Diffuse emission processes
- inverse Compton
- Bremsstrahlung
- nuclear interactions lines
- $\pi^0$ decay (> 300 MeV)
Spatial correlation between gaz and $\gamma$-rays

**Observations (EGRET):**
- large scale spatial distribution well modelled by combination of ISM phases (assuming $I \propto \rho^2$)
- fraction of unresolved point sources is small (unless distributed like the interstellar gas)
- spectrum does not vary (within relatively small uncertainties) in the Galaxy
- deviations from perfect fit

**Implications:**
- Gamma-Rays probe galactic CR and ISM distributions
- CR electron-to-proton ratio roughly constant throughout Galaxy
- assumption of dynamic balance ($I \propto \rho^2$) between ISM and CR is reasonably correct
  (large matter density implies larger magnetic fields, allowing for larger CR energy density)
Spectral modelling: The conventional model

Model
- based on non-\(\gamma\)-ray data only
- fits only between 30 - 500 MeV

Electron spectrum
- \(E^{-1.6} : E < 10\) GeV
- \(E^{-2.6} : E > 10\) GeV
- agrees with locally measured spectrum
- satisfies synchrotron spectrum

Proton spectrum
- \(E^{-2.25}\)
- agrees with locally measured spectrum

Model (Strong et al. 2000)
### Spectral modelling: Hard CR spectrum model

**Model**
- allow for harder e\(^{-}\) and p spectrum
- does not fit <30 MeV (& GeV bump)

**Electron spectrum**
- \(E^{-1.8}\) (harder w/r C-model above 10 GeV)
- differs from locally measured spectrum (high-energy e\(^{-}\) undergo rapid E-loss)
- satisfies synchrotron spectrum (> 10 GeV spectrum unconstrained)

**Proton spectrum**
- \(E^{-1.8}\) : \(E < 20\) GeV (harder w/r C-model)
- \(E^{-2.5}\) : \(E > 20\) GeV
- agrees with locally measured spectrum (solar modulation allows for some freedom at low energies)
Spectral modelling: Steep low-energy e⁻ model

Model
- allows for more low-energy e⁻
- ad hoc (no observational evidence)
- large power input into ISM (ionisation)

Electron spectrum
- $E^{-3.2} : E < 200\ \text{MeV}$ (steeped w/r C-model)
- $E^{-1.8} : E > 200\ \text{MeV}$ (like HEMN model)
- differs from locally measured spectrum (high-energy e⁻ undergo rapid E-loss)
- satisfies synchrotron spectrum ($< 1\ \text{GeV}$ spectrum unconstrained)

Proton spectrum
- $E^{-2.25}$ (C-model)
- agrees with locally measured spectrum
A dark-matter scenario

(de Boer et al. 2005)

Possible explanations of GeV excess
- different CR spectrum than local
- unresolved point-sources
- EGRET calibration error
- Dark Matter

Dark Matter Model
- WIMP annihilation: $\chi + \chi \rightarrow q + q \rightarrow \pi^0 \rightarrow \gamma$
- WIMP mass 50 - 100 GeV best fits the EGRET data
- Derive WIMP distribution from $\gamma$-ray distribution
- DM in halo and 2 elliptical rings ($R = 4$ & 14 kpc)
- DM distribution can explain rotation curve

But ... (Bergström et al. 2006)
- WIMP annihilation should also produce antiprotons
- Observed antiproton flux much too low w/r model
- Strange DM distribution (resemblance to baryon distribution with bulge, thin and thick disk)
The first VHE survey of the Galaxy

**H.E.S.S. survey**
- longitudes ±35°, latitudes ±4°
- 10 sources from which 8 are new (all spatially resolved ⇒ extended emission)
- clustering of sources along the galactic plane (young population)
- some plausible associations with SNRs and pulsars
VHE diffuse emission

**H.E.S.S. discovery of diffuse emission**
- Subtract point-like emission from sources
- Extended emission (in I and b) along gal. Plane
- Correlates with molecular gas (CS)
- Power law spectrum: $\Gamma = 2.3 \pm 0.3$

**Interpretation**
- $\pi^0$ decay following CR interaction with ISM
- Flux higher and harder than expected $\Rightarrow$ recent (~10,000 yr) CR acceleration at GC and diffusion
The nature of galactic X-/γ-ray emission

The nature of galactic X-/γ-ray emission

The nature of galactic X-/γ-ray emission

The nature of galactic X-/γ-ray emission

The nature of galactic X-/γ-ray emission

The nature of galactic X-/γ-ray emission

The nature of galactic X-/γ-ray emission

The nature of galactic X-/γ-ray emission

The nature of galactic X-/γ-ray emission

The nature of galactic X-/γ-ray emission

The nature of galactic X-/γ-ray emission

The nature of galactic X-/γ-ray emission

The nature of galactic X-/γ-ray emission

The nature of galactic X-/γ-ray emission

The nature of galactic X-/γ-ray emission

The nature of galactic X-/γ-ray emission

The nature of galactic X-/γ-ray emission

The nature of galactic X-/γ-ray emission

The nature of galactic X-/γ-ray emission

The nature of galactic X-/γ-ray emission

The nature of galactic X-/γ-ray emission

The nature of galactic X-/γ-ray emission

The nature of galactic X-/γ-ray emission

The nature of galactic X-/γ-ray emission

The nature of galactic X-/γ-ray emission

The nature of galactic X-/γ-ray emission

The nature of galactic X-/γ-ray emission

The nature of galactic X-/γ-ray emission

The nature of galactic X-/γ-ray emission

The nature of galactic X-/γ-ray emission

The nature of galactic X-/γ-ray emission

The nature of galactic X-/γ-ray emission

The nature of galactic X-/γ-ray emission

The nature of galactic X-/γ-ray emission
Summary

Hard X-ray emission - GRXE (E < 200 keV)
• observationally, a diffuse (unresolved) component remains
• theoretically, diffuse emission is difficult to understand (pressure, gravitational binding)
• spatial distribution and spectrum consistent with population of weak X-ray point sources

Soft γ-ray regime (200 keV < E < 511 keV)
• diffuse positronium annihilation dominates (bulge region)
• still no e^+ point sources detected (but diffusion make annihilation probably inherently diffuse process)

MeV domain (1 MeV < E < 30 MeV)
• ^{26}\text{Al} and ^{60}\text{Fe} radioactive decays lead to diffuse line emission
• source of continuum emission unclear (unresolved MeV point sources?)

GeV domain (30 MeV < E < 30 GeV)
• diffuse emission explained by CR interaction with ISM
• spectrum leaves room for additional components (Dark Matter?, point sources?)

TeV domain (E > 30 GeV)
• individual point sources identified (SNRs, pulsars)
• diffuse emission component that correlates with molecular clouds
Bibliography (some selected articles)

• Galactic ridge X-ray emission

• Soft gamma-ray emission

• Positron annihilation

• Galactic radioactivity
  Diehl et al. 2006, Nature, 439, 45

• MeV and GeV galactic diffuse emission

• TeV galactic diffuse emission
  Aharonian et al. 2006, Nature, 439, 695