hard X-ray and soft $\gamma$-ray Galactic diffuse emission

What do we know after 6 years of Integral?

& a very short status on the future of the mission

R. Terrier APC
Diffuse emission 6 years ago

\(~10\ \text{MeV} < E,\)
- truly diffuse processes

\(~300\ \text{keV} < E < 511\ \text{keV}\)
- Positronium decay (in the Galactic bulge)

\(a\ \text{few keV} < E < ~300\text{keV}\)
- Level of point sources contribution uncertain

Possible diffuse processes:
- IC on low E e\(^-\) population: too low \((\text{radio constraint})\)
- Bremsstrahlung of low E e\(^-\) population: too much ionization & high power

An important contamination from point sources is assumed
Diffuse emission 6 years ago

OSSE (>50 keV) : collimator with no imaging capability
measure total Galactic emission (sources + diffuse)  (Kinzer et al. 1999)
necessity to make simultaneous observations with “imaging” telescopes:
- SIGMA (coded mask instrument):  (Purcell et al. 1996)
  Sensitivity of ~ 30 mcrab, 40 to 60% of total emission is diffuse
- RXTE:  (Valinia, Kinzer & Marshall 1999)
  in Scutum arm (l=30°)
  ~50% and 70% of diffuse at 60 and 100 keV

Low energy (<20 keV) measurement of Galactic ridge emission

If the residual emission is due to discrete sources, 10 sources of flux $5.10^{-3}$ ph./cm2/sec/MeV at 100 keV must be present in the field of view of OSSE to make up the spectrum. Because no such class of sources with a uniform space density in longitude is known, the emission at about 100 keV is probably of diffuse origin

Pohl (1998)
**INTEGRAL**

**Imager: IBIS/ISGRI**
- 15keV-2 MeV
- 16000 pixels CdTe
- FoV: 9° (tot. coded)
- PSF : 12' (FWHM)
- sensitivity ~ 1mCrab

**Spectrometer SPI**
- 20 keV – 10 MeV
- 19 detectors Ge
- E resolution 2.5 keV @ 1 MeV
- PSF 2.6° (FWHM)
- FoV: 16° (tot. coded)
The IBIS/ISGRI sky (20-60 keV)

~400 sources
mostly LMXB & HMXB
AGNs
Cvs
Pulsars/AXP/PWNe
SNRs
tens of unidentified
IBIS/Isgri is able to resolve a large number of sources emitting in the hard X-ray range.

Using a lightbucket technique, Lebrun et al. (2004) showed that more than 80% of the total Galactic flux is due to point sources under 100 keV.

Lebrun et al. (2004)
Terrier et al. (2004)
Using a similar lightbucket technique, Krivonos et al (2007) studied the morphology of the residual 15% of the total Galactic flux which is not resolved in point sources.

The morphology is well correlated with DIRBE 4.9 μm maps.

*Krivonos et al. (2007)*
Diffuse emission (E<100 keV) with Integral?

ISM is not a good tracer of residual ridge emission

Hard X ray ridge emission follows stellar mass distribution

\[ \frac{F_{17-60 \text{ keV}}}{F_{\text{NIR}}} \sim 7.5 \times 10^{-5} \]

Emissivity: \(10^{27} \text{ erg/s/M}_\odot\)

Residual emission due to unresolved faint sources such as Cvs (similarity of the spectra)

Krivonos et al. (2007)
Low energy diffuse emission likely entirely due to point sources (most still unresolved)
Recent result by Revnivstev et al (2009) shows that up to 90% of 6.7 keV plasma is in fact due to faint stellar population as well.

What about diffuse emission >100 keV?
Analysis using SPI (more sensitive at high energies) shows that there remains a hard power law component dominant above 100 keV

*Strong et al (2005), Bouchet et al. (2005 & 2008)*

Images obtained through a model fitting approach

*Bouchet et al. (2008)*
Diffuse emission with Integral

$|l| < 30^\circ$

Hard power law: $\Gamma = 1.55$

Important contribution from 511 keV line and positronium

Marginally consistent with Krivonos et al. non-detections up to 200 keV

Origin?

_Bouchet et al. (2008)_

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Origin of hard power law component?

Unresolved faint and hard point sources (e.g. Pulsars and AXPs)

sub-GeV $e^+$ and $e^-$ IC on CMB photons (Porter et al 2008)

Secondary leptons dominant $< 1$ GeV

Taking into account the secondaries in once optimized model overpredicts hard X-ray component

Porter et al. (2008)
Origin of hard power law component?

Origin of the discrepancy?

So called optimized model is no longer valid since Fermi result of the absence of GeV excess

Primary electron source spectrum < a few GeV

Latitude distribution of the electrons w.r.t. SPI measurements

$|b| < 5^\circ$

Porter et al. (2008)
Flux of $\sim 10^{-3}$ ph/cm$^2$/s in 511 keV line $\rightarrow 10^{43}$ s$^{-1}$ annihilations at GC distance


Distribution 9° (FWHM) gaussian profile around Galactic Centre. Origin?
A fainter contribution from the Galactic disk

$(\sim 25\%$ of which is due to decay chain of $^{26}$Al)

Recently, Weidenspointner et al (2008) have claimed detection of asymmetry in disk distribution

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Maximum entropy image of the line emission

511 keV emission: asymmetry

Isgrì detected LMXBs → $e^+$ origin from a few 100 hard LMXBs?

Weidenspointner et al. (2008)
Diffuse emission from the Central Molecular Zone

6.4 keV Ka Fe line

60-80 keV

VHE
Diffuse emission from Sgr B2 cloud

IGR J17475-2822 detected at more than 50 $\sigma$

Measured 20 - 100 keV flux: $F = 2.4 \times 10^{-11}$ erg cm$^{-2}$ s$^{-1}$

$\Rightarrow$ $L_\gamma = 2 \times 10^{35}$ erg/s

Fitted position in good agreement with Sgr B2 cloud

IBIS PSF encompasses also nearby M0.74-0.09 cloud

Point sources in the vicinity are too faint to explain the Isgri source
Fluorescence and Compton scattering of a very bright nearby source

\[ \text{e.g. Churazov et al (1999), Murakami et al (2000)} \]

At <10pc distance, \(10^{37}\) erg/s flare \(~10\) yr ago is required to account for measured luminosity

No such source in the vicinity of Sgr B2

At 100pc distance, \(10^{39}\) erg/s flare \(~300\) yr ago is required to account for measured luminosity

Was Sgr A* more active than today? (6 order of magnitude increase)
Origin of diffuse emission from the CMZ?

Intense low energy cosmic-rays electrons (LECRE) \textit{Valinia et al (2000)}

- Fe Ka line EW too small
- Required e- luminosity comparable to cloud bolometric luminosity because of large Coulomb losses

\textit{Crocker et al, (2007)}
GMC Sgr B2: light curve: 6 years of deep monitoring

Flux is not stable

Linear flux decay preferred at the $4\sigma$ level: typical time scale $\sim 20$ yrs

Terrier et al, (2009)
Instruments are still performing well:
  SPI: 16 Ge detectors still working on SPI
  ISGRI: <1000 noisy pixels out of 16000
      gain decrease by ~ 15%

CR Background has increased significantly,
Solar cycle should decrease this contribution but there is some delay...

Mission extension:
  OK till end 2010
  Budget up to 2012
  Discussion on possible extension in September

Last AO first round results are out:
  it is possible to ask for data rights for sources in the FoV of key
  program observations
Integral AO-7: Key programmes

First round of observation proposals selection has been performed:

~20 large programmes (>1 Ms) to be performed from Oct 09- Dec 10

Among these some dedicated or possibly relevant to diffuse emission studies:

• Probing relativistic electrons in the Galaxy and its halo (*Strong*)
• INTEGRAL monitoring of the Galactic Bulge region (*Kuulkers*)
• Confirming the Asymmetry of the Positron Annihilation Radiation from the Inner Galactic Disk (*Weidenspointer*)
• Deep Galactic Anticentre Survey (*Ubertini*)
• Broad view on high energy Galactic background (*Sunyaev, Krivonos & Tyngakov*)
• Nucleosynthesis and positron annihilation in the Cygnus region (*Martin*)

Data rights open for these programs: Proposals to be sent before July 3rd

Documentation and complete list of pointings at:
http://www.sciops.esa.int/index.php?project=INTEGRAL&page=AO7S
Objective:

High latitude distribution of the hard power law component of diffuse emission

A probe of the distribution of cosmic-ray electrons in the Galaxy

Try to solve the discrepancy with the overprediction of sub GeV secondaries IC in GALPROP

a multi-year scan covering a wide latitude range in the inner Galaxy

A link with the Fermi LAT
AO7: Confirming the Asymmetry of the Positron Annihilation Radiation from the Inner Galactic Disk (Weidenspointner)

Objective:
- High latitude distribution of the hard power law component of diffuse emission
- A probe of the distribution of cosmic-ray electrons in the Galaxy
- A multi-year scan covering a wide latitude range in the inner Galaxy
- A link with the Fermi LAT
Integral (along with other instruments) has completely changed the picture of the diffuse emission in the hard X-ray and soft gamma-ray domain.

No soft and bright ridge emission <100 keV: a collection of faint sources distributed as stars: magnetized CVs

A remaining hard ($\Gamma=1.55$) power law component along the Galactic plane:
  unresolved hard sources?
  IC of GeV electrons on CMB photons?

e+/e- annihilation signal distributed in the bulge + possibly asymmetric disk component
  e+ created by hard LMXBs?

Emission from Sgr B2 GMC in the Galactic Centre likely due to reflection from a past flare in the GC vicinity
  Low energy CR probably not dominant there

Integral still doing well: propose your favorite sources in AO7 round 2!!!
How to measure hard X-ray and soft $\gamma$-ray Galactic diffuse emission?

Separating point sources from diffuse emission

R. Terrier APC
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source

Coded mask

Position sensitive detector
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source 2

Coded mask

Position sensitive detector

source 2

Coded mask

Position sensitive detector
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observation

deconvolution

transmission
Diffuse emission with a coded mask instrument?

Objectives:
resolve point sources component
Image residual diffuse emission
Coded mask imaging process suppresses structures larger than the PSF
(12' for IBIS, 2.6° for SPI)

\[ \alpha R^{-2} \]
GC ~ 25 keV (Isgri)
Standard analysis
Many point sources
Diffuse?
Diffuse emission with a coded mask instrument?

GC > 200 keV (Isgri)
Standard analysis
Large diffuse structure
But not aligned with Galaxy!!
Objectives:
- resolve point sources component
- Image residual diffuse emission

Coded mask imaging process suppresses structures larger than the PSF (12' for IBIS, 2.6° for SPI)

Several techniques to overcome this difficulty:

**Lightbucket:**  
Use instrument as a collimator for the total flux but use its imaging capabilities to resolve point source fluxes

**Model fitting:**  
Bouchet et al. (2005)  
Fit a diffuse model made of templates (e.g. CO & HI) plus point sources

**Likelihood technique:**  
Bouchet et al. (2008)  
Fit diffuse fluxes in large spatial bins + point sources

**Iterative deconvolution:**  
Knödelseder et al (2007)  
Use input source list and apply constrained model
On background subtraction

Whatever the approach: **Background is your enemy!**

Use CR counters on board to evaluate CR activity and model the induced bkg in the detectors.

CR activity dependent on solar activity:
- 11 yr cycle
- flares
- rotation period
Light bucket: Using IBIS as a collimator


Compare measured count rate to expected count rate from detected sources:
- Cosmic-ray induced BKG (especially time varying BKG)
- Isotropic & constant component (Cosmic diffuse BKG + internal BKG)
- Point sources & diffuse Galactic emission

Typical algorithm:
Detect point sources
Calibrate bkg model on high latitude data
For each pointing
  • Correct for isotropic and time varying backgrounds
  • Estimate precisely source count rate in the detector
  • Compute residual emission (isotropic + Galactic "diffuse")
  • Add flux to map using instrument acceptance: resolution = FoV size

Difficulties:
Number of parameters (up to 120 sources in foV)
Poor angular resolution
Determine detector count rate correlation with CR calibration using high latitude observations $|b|>30^\circ$ (no sources, no Galactic emission)

Uncertainties in this relation limits the accuracy of flux correction

Allows to evaluate isotropic (CXB) & constant BKG (activation in satellite)
Light bucket: detecting sources

Apply “standard” analysis techniques
Source detection algorithm
Estimating the sources count rate

To estimate the total point sources flux through 'ISGRI collimator':

For each pointing:

- For all detected sources
  - Use the *estimated count rate* through imagery
  - Correct for acceptance & absorption using the source position in the FOV

- Sum all sources count rates

- **Normalize total flux using crab observations** to correct for inaccuracies in imagery flux calibration

Systematics are introduced by this calibration
Longitude profiles

|b|<5°

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Longitude profiles

|b| < 5°

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Latitude profiles

Sco-X1: large angle acceptance pb

$|l| < 20^\circ$
Latitude profiles

\[ |\| < 20^\circ \]

- Graph showing counts per second against latitude with data points indicating shielding transparency larger for different energy levels.

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Remaining diffuse flux

\begin{itemize}
  \item 20 – 40 keV $8.6 \pm 2.9 \text{ c/s}$ \rightarrow $14 \pm 4.5\%$ of total Galactic emission
  \item 40 – 60 keV $0.2 \pm 1.1 \text{ c/s}$ \rightarrow $<19\%$ (3\(\sigma\)) of total Galactic emission
  \item 60 – 120 keV $0.7 \pm 1.3 \text{ c/s}$ \rightarrow $<27\%$ (3\(\sigma\)) of total Galactic emission
  \item 120 – 220 keV $-0.3 \pm 0.6 \text{ c/s}$ \rightarrow $<52\%$ (3\(\sigma\)) of total Galactic emission
\end{itemize}

Reconstruct spectrum

usual forward folding technique using arf and rmf

Difficulty with IBIS/Isgri: decrease of photoelectric efficiency $> 100$ keV

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Light bucket: making an image

Put residual flux at optical axis position and distribute it along your detector acceptance.

Resulting structure has a spatial resolution of ~20°
   is influenced by dithering pattern.
Model fitting

Assume diffuse emission spatial distribution follows typical tracers
Typically CO & HI at high energies and IR at low energies (eg Bouchet et al)

Typical algorithm:
- Source detection (using one or several instruments)
- In each pointing
  - Estimate Bkg contribution using precalibrated model (high latitude data)
  - Fit source fluxes + diffuse component on bkg subtracted dataset

Difficulty of number of parameters:
- SPI has 19-16 active detectors: only 12 sources can vary on a scw basis
- Validity of the model used?
Model fitting

Assume diffuse emission spatial distribution follows typical tracers
Typically CO & HI at high energies and IR at low energies (eg Bouchet et al)
Model-independent maximum likelihood technique

Assume diffuse emission spatial distribution follows Galactic plane (somewhat reasonable assumption)
  – e.g. 16x2° bins in Bouchet et al (2008)

Typical algorithm:
  – Source detection (using one or several instruments)
  – In each pointing
    • Estimate Bkg contribution using precalibrated model (high latitude data)
    • Fit source fluxes + template diffuse component on bkg subtracted dataset
  – Using fitted sources fluxes
    • Determine diffuse fluxes in each spatial bins

Difficulty of number of parameters:
  – SPI has 19-16 active detectors: only few sources can vary on a scw basis
Model - independent maximum likelihood technique

Assume diffuse emission spatial distribution follows Galactic plane (somewhat reasonable assumption)
  - e.g. 16x2° bins in Bouchet et al (2008)
Summary & future prospects

Main difficulties in this energy range:

**Point source contamination:**
Need sensitive high resolution instrument

**High background environnement**
Need precise internal bkg model (including CR induced bkg and also internal activation)

**Impossible to make direct images of very extended structures:**
Light bucket: poor angular resolution
Model fitting : large number of parameters
up to 120 sources per pointing (a significant number of which is varying)

To give a more precise determination of the level of diffuse emission:
- Need to use all instruments on board Integral:
  - Simultaneous independent measurements (sources & diffuse)
- Improve bkg determination
- logN-logS studies to evaluate undetected sources contribution

Volunteers?