The Galactic Radiation Field

- CR electrons and positrons lose energy via IC $\Rightarrow$ gamma ray production in ISM (INTEGRAL, GLAST, TeV)
  - For this we need both the spectral energy distribution (SED) + the angular distribution
  - IC gamma rays $\Rightarrow$ anisotropic RF gives enhancement/deficit compared to isotropic RF (M&S ApJ 528,357)

- Gamma rays from SNRs
  - Different locations in Galaxy give enhancements due to relative strength of optical/infrared/CMB (PMS ApJL 648,29)

- Gamma ray absorption at TeV energies
  - Pair production on ISRF by gammas attenuates high energy spectra (MPS ApJL 640,155)


- UV Heating of clouds in the Galaxy, etc.
- Extraction of EBL (?)
Overview of Data

- **Earliest data `available' in UV/opt in publications in 1960/70s**
  - UV/optical (papers by Witt et al. 1967 onward)
  - S2/68 (TD1) observations (UV skymaps) by Gondhalekar, Phillips, & Wilson (A&A 85, 272), update ~1990 (?)
  - UV RF by Henry and co-authors from 1970s onwards
  - SPEAR UV data (soon?)

- **All-sky Infrared data has come from IRAS and COBE**
  - IRAS many papers (authored by people at this meeting?)
  - DIRBE papers by Dwek, Arendt, Sodroski, et al. (late 90s)
  - Data is available for download ⇒ not the case with UV/OPT
  - http://lambda.gsfc.nasa.gov for COBE data products
  - http://irsa.ipac.caltech.edu for IRAS, etc.

- **No all-sky from other instruments (e.g., Spitzer) ⇒ selected regions only (GLIMPSE, MIPSGAL). Planck all-sky over next 18 months**
Overview of calculations

• First calculation done for UV/OPT by Witt & Johnson (1973)
• Henry (ApJS 33, 451) integrated stellar light from catalogues
• Drapatz (A&A 75, 26) calculated FIR emission of disc
• Modelling of UV with disc+LF by Caplan & Grec (A&A 78, 335)
• Modelling of UV by Mattila (A&A 82, 373)
• MMP (A&A 105, 372; A&A 128, 212) ← second paper is most highly cited on subject and first time stellar emission + dust emission treated, but only give for R = 5, 10 kpc (R⊙ = 10 kpc)
• Bloemen (A&A 145, 391) ← explicitly for gamma rays!
• Cox, Krügel, & Mezger (A&A 155, 380)
  - also see Cox & Mezger (ARA&A 1, 49)
• Chi & Wolfendale (J.Phys.G. 17, 987) ← extended MMP to give energy density for (R, z), no SED
• UV modelling of Galaxy by Brosch (MNRAS 250, 780)
• Porter (Ph.D., 1999) and Strong et al. (2000)
Basic Ingredients of Calculation

- The ISRF is the result of radiative transport through the ISM of the light emitted by stars in the Galaxy
  - The distributions of stars and dust are non-trivial, and the dust is not optically thin, so we need to do a radiative transport calculation ⇒ no simple line-of-sight integrals!
- Starlight is scattered and absorbed by dust in the ISM
- Absorbed starlight is re-emitted by dust grains of different sizes from NIR to FIR
- To do the calculation (properly) we need to construct
  - Stellar luminosity distribution model
  - Dust abundance and distribution model
  - Do the radiative transport calculation using some method either involving ray tracing or Monte Carlo
Stellar Components

- Stars distributed in bulge, thin and thick disc, halo
  - Triaxial bulge (ala Besancon model), but there could be `thin' bar, etc.
  - Thin disc incorporates smooth disc, spiral arms, ring
  - Thick disc distinct population to thin disc (merger origin?)
  - Halo, low density also maybe from mergers
- Geometric parameters have a large degree of uncertainty
  - Thin disc radial scale length ~2-4 kpc, may have a cutoff, maybe not
  - Thick disc scale height 0.5-1.5 kpc, etc.
  - Halo ellipticity could be ~0.6-0.9, etc.
- Each component has a mix of stellar types characterised by a luminosity function (see next slide)
  - Even the scale heights of different stellar types within, e.g., the thin disc, are uncertain
Represent LFs using source table for stars of usual spectral types (O, B, A, G, ..) and luminosity classes (I, .., V)

Component LFs obtained by applying weights to source types in table - obtain consistency across different wavebands if available
Dust Abundances and Distribution

- **Dust mixture**
  - PAH/graphite/silicate
  - W&D size dist., D&L dust properties
  - Dust/gas ~ 1:126
  - Grains assumed spherical (not the realistic case ...)
    - Potential signature in polarised maps (Planck?)

- **Dust distribution**
  - Uniform mixing (Bohlin 1978)
  - Follow gas distribution (or D&S dist., or ...)
  - Metallicity gradient ~0.04-0.07 dex/kpc ⇒ factor 2-4 enhancement from solar circle
Radiative Transfer

Dust is not optically thin for starlight so we want to solve the radiative transport equation:

\[
\frac{dJ(\lambda, s, \hat{s})}{ds} = -n_H(s) \sigma_{ext}(\lambda) J(\lambda, s, \hat{s}) + \epsilon_*(\lambda, s, \hat{s}) + \epsilon_{scat}(\lambda, s, \hat{s}) + \epsilon_{abs}(\lambda, s, \hat{s})
\]

- Extinction
- Stars
- Scattered into beam
- Dust emission into beam

Early versions used an iterative method -> calculate stellar emission, scattered, then feed stellar + scattered (optical) into dust heating calculation, calculate infrared

**Convergence is moderate with the issue of continued iteration.**

**Much better is Monte Carlo method which was implemented in 2008 and is used today.**
Overview of ISRF Modelling

• FRaNKIE = Fast Radiative transfer Numerical Kode for Interstellar Emission

• Takes input: stellar and dust distributions with frequency dependence
  - These can have arbitrary components, completely user specified
  - Current model → 4 stellar components (bulge, thin disc, thick disc, halo), 3 dust grain types (PAH, silicate, graphite) uniformly mixed with gas in ISM, use analytic gas model from galprop

• Monte Carlo radiative transfer calculation implements full treatment of scattering, absorption, and re-emission (via transient and equilibrium heating of grains) → uses cross sections and other data from supplied grain model for this

• Geometry: 2D, 3D spherical, cartesian → user specified spacing

• Output of calculation in full range of photometric filters (more can be easily added) + full wavelength dependence
Local ISRF SED (R = 8.5 kpc)

Model SED consistent with broad band data

Used since Porter et al 2008
Varying Dust Content

- Metallicity gradient can be adjusted to study simple variations in dust content
  - Tried 'maximal' and 'minimal' (flat) gradient for recent study of SPI data
- This mainly alters the UV and the 'cold' dust emission in the FIR
Data: DIRBE near-far IR

(240 μm not shown)
Example Model Maps (in DIRBE filters)

- 1.25 μm
- 2.2 μm
- 3.5 μm
- 4.9 μm
- 12 μm
- 25 μm
- 60 μm
- 100 μm
- 140 μm

(240 μm not shown)
Data vs. Model(s)

Data

Standard ISRF

Bulge x10

1.25 μm

4.9 μm

240 μm
Fermi-LAT Project

Data vs. Model(s)

Data

1.25 µm

Standard ISRF

1.25 µm

Bulge x10

1.25 µm

4.9 µm

4.9 µm

4.9 µm

240 µm

240 µm

240 µm
Energy Density at GC and Local

Data: DIRBE and FIRAS
Angular Distribution at Different R, z

Standard

1.25 μm  240 μm

R, z = (2, 0) kpc

Bulge x10

1.25 μm  240 μm

R, z = (2, 0) kpc

R, z = (2, 1) kpc

R, z = (2, 1) kpc

Coordinate system: directed toward GC
Fig. 1.—Angles involved in the ICS process: $(\theta, \phi)$, polar and azimuthal angles of the incoming photon; $(\kappa, \psi)$, the same for the electron; and $R_s$, observer’s position. See text for more details.
Standard ISRF model (halo 10 kpc)

50 MeV

35 GeV
Ratio Bulgex10/Standard (10 kpc halo)

Aniso skymap  aniso sum  iso sum

50 MeV

35 GeV
Moving Beyond 2D ISRF

2.2 μm

100 μm

(0, 0, -20) kpc

eV cm^-2 s^-1 sr^-1

(8.5, 0, 0) kpc

MJy sr^-1

DIRBE data

MJy sr^-1

Dec 6, 2011
Moving Beyond 2D GALPROP (3D Source Model)

Inverse Compton (2D)

Inverse Compton (3D)

43 MeV

247 GeV

Uses spiral arm + GC component from NE2001 model for HII as source distribution (same spiral arms for OB stars in ISRF model)
Summary

- The details of the ISRF matter for the calculation of the broadband diffuse emission of the Milky Way (and other galaxies)
- With the current modelling, there is degeneracy for the parameters which is responsible for uncertainty in the SED, particularly within the innermost 4 kpc
- Some increase in the bulge (compared to what has been used up to now) seems to be necessary BUT we also need to take into account the 3D distribution because this determines the position angle wrt Earth–GC line (also spiral arms)
- The data cubes for the standard ISRF are available as part of the data set required for GALPROP to run
  - Different versions are available, appropriate for various versions of GALPROP that have been produced
- The ISRF angular distribution is required for the anisotropic IC calculation, which gives a different (IC) angular distribution for the same radiation field modelling parameters
Some ideas for the future 1

- The 3D ISRF modelling can be easily extended to other galaxies where there is no (even approximate) axisymmetry, e.g., LMC, SMC, or MW analogues, e.g., M31
- Using 3D details, e.g., spiral arms (OB stars), as putative source distributions for input to a 3D GALPROP calculation yields some interesting differences than the 2D assumption that we have been using (much more freedom), but has the potential to more (in)accurately describe what we see (c.f. Low-level residuals shown by Gulli yesterday)
- To optimise the calculations for these cases we need to do some code work
  - Variable grid (intelligent voxelisation of the calculation volume)
  - Provide handles to enable using different models for sources, gas instead of the hard-wiring that is in place currently
Some ideas for the future 2

• We are able to model other galaxies now, and this is especially useful with the LAT resolving of the LMC and the detections of the SMC and M31 (sufficient resolving by the end of the mission?)

• The LMC/SMC are very different systems to the MW, and we are extending GALPROP beyond a simple beam/target code to treat ISM physics caused by CRs, and possible back reactions on the CRs themselves (c.f. Misha's question about propagation yesterday)
  - This gives one idea where to go beyond simply modelling the Milky Way
  - Potential to treat local CR sources, clouds/star-formation regions, and large-scale CRs in the same framework would be very interesting but not done up to now