CR induced interstellar emissions

– with focus on the Milky Way –

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Overview of lecture

- Introduction, cosmic rays (CRs), the interstellar medium (ISM), and high-energy interstellar emission
- Cross sections, an overview
- The targets and how to determine their distribution
  - Interstellar gas
  - Interstellar radiation field
- CR fluxes, how to model
- Application to *Fermi*–LAT data

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What you should understand after the lecture

Have a general understanding of the matter and a resource to dig deeper.

Between the stars

Fun fact

Our Milky Way mass is comprised of mostly dark matter ($\sim 95\%$) and stars ($\sim 5\%$).

Credit: ESO/S. Brunier

Between the stars

Fun fact

Our Milky Way mass is comprised of mostly dark matter ($\sim 95\%$) and stars ($\sim 5\%$).

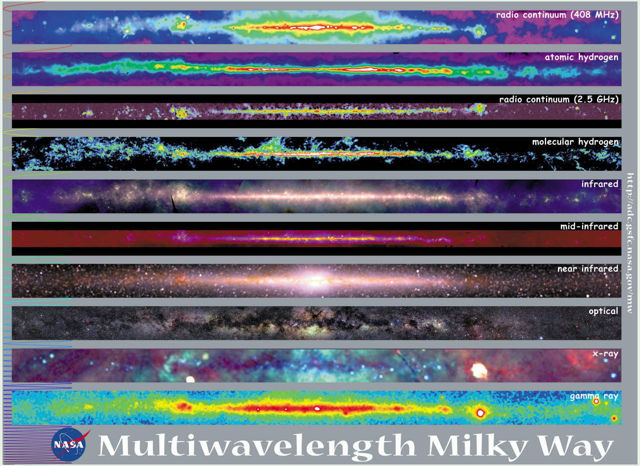
This lecture will focus on the rest ($\sim 0.5\%$) that is the ISM.

The space between the stars is permeated with:

- Tenuous gas and dust
- Radiation from stars that is reprocessed by the dust
- A weak magnetic field
- Cosmic rays

An illustration

The plane of the Milky Way

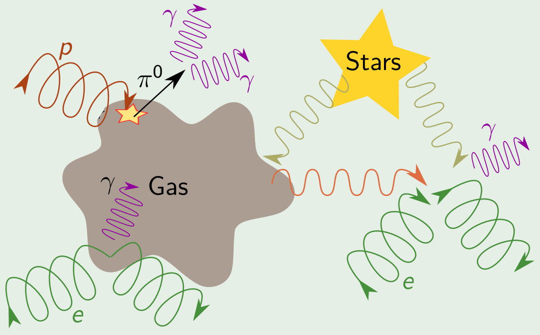


Credit: NASA

- An older viewgraph, but still shows interesting features.
- Connection between different wavebands not obvious:
  - Black patches in optical correlate with molecular hydrogen.
  - Infrared and γ-ray maps are similar.
  - So is 408 MHz and γ-ray maps.
- Why?

High-energy interstellar emission

Emission processes

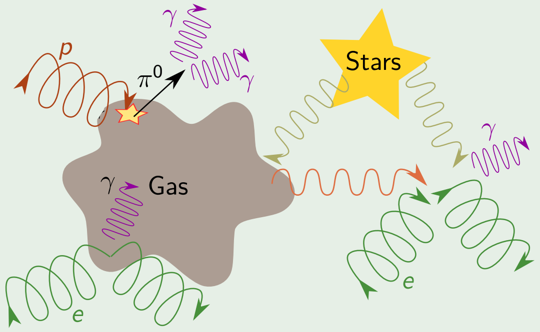


Typical definition

- Interstellar emission arises from interactions between cosmic-rays (CRs) and the interstellar medium (gas and radiation).
- CR nuclei:
  - π^0–decay from interactions with gas.
- CR electrons (e^+ and e^-):
  - Bremsstrahlung from interactions with gas.
  - Inverse Compton (IC) from interactions with radiation.

High-energy interstellar emission

Emission processes



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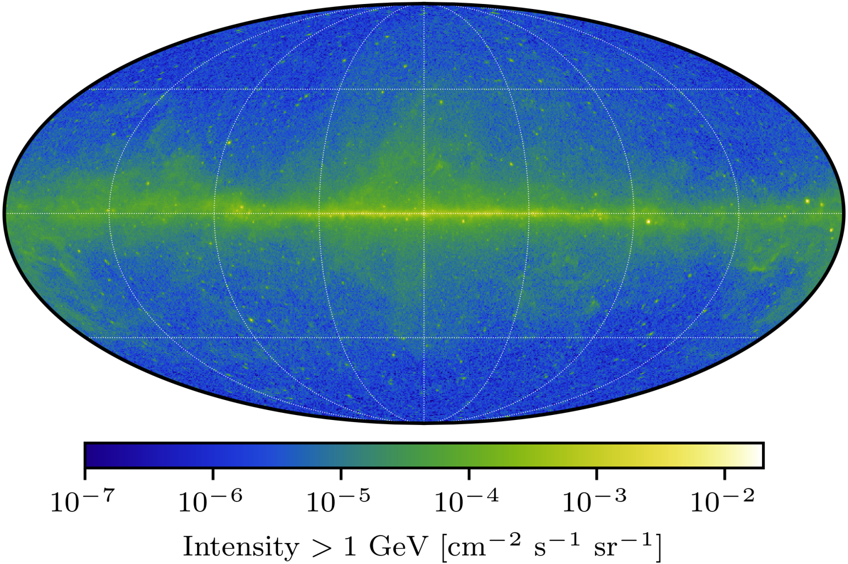
Synchrotron radiation

Electrons (and positrons) also produce synchrotron radiation on the magnetic field.

8 years of LAT data above 1 GeV (P8 PSF3)



High-energy interstellar emission as a tool

- Unlike CRs, γ-rays trace directly back to their origin.
- The Milky Way is transparent to high-energy γ-rays.
  - Exception are γ-rays with energies above $\sim$ *TeV* that are absorbed by the infrared radiation in the Milky Way.
- The total emission is therefore (simplified) found from integration along sightlines

$$\int F_c \sigma_{c\to\gamma} n_t ds$$

  where F_c is the CR flux, $\sigma_{c\to\gamma}$ is the production cross section of γ-rays, and n_t is the target density.
- It can provide a wealth of information
  - Useful to estimate F_c given knowledge about $\sigma_{c\to\gamma}$ and n_t.

γ-ray-production cross sections – nuclei-nuclei

- Several estimates available for nuclei-nuclei interactions
  - Dermer, C.D 1998, ApJ, 307, 47: Isobaric treatment at low energies (Stecker 1970) and scaling (Badhwar 1986) at higher energies.
  - Blattnig et al. 2000, PhRvD, 62,9: Parameterization of observational data based on older results.
  - Kamae et al. 2006, ApJ 647, 692: Inelastic cross section, diffraction dissociation process, Feynman scaling violations, and baryon resonances.
  - Huang et al. 2007, Astropart. Phys, 27, 5: DPMJET
  - Shibata et al. 2014, Astropart. Phys, 55, 8: Similar to Dermer, extended to higher energies.
  - Mazziotta et al. 2016, Astopart. Phys, 81,21: FLUKA
- Differences of the order of 10%
- Many use accurate proton-proton and then scale for other nuclei (nuclear enhancement factor)
  - Mori, M 2009, Astrop. Phys., 31, 5: DPMJET-III to calculate the factor
  - Kachelriess et al. 2014, ApJ, 789,2: QGSJET-II-04 and EPHOS-LHC particle codes used to calculate the factor

Example nuclear enhancement factors

Kachelriess et al. 2014

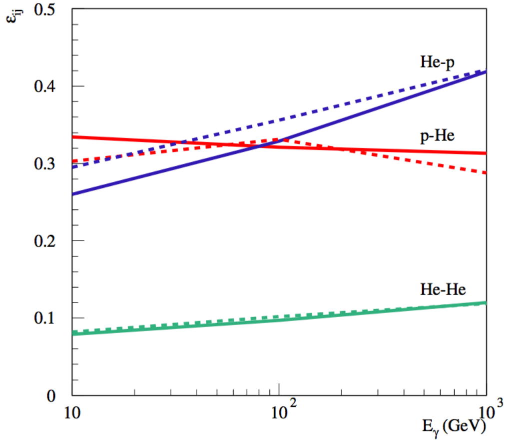


Figure 1. Partial contributions ε_{ij} to ε_M for several reaction channels, as indicated in the plot, calculated with QGSJET-II-04 (solid lines) and EPOS-LHC (dashed lines) models.

Mori 2009

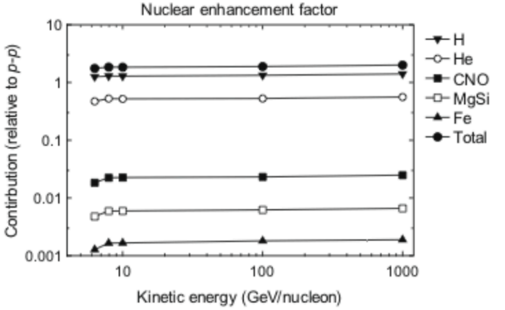
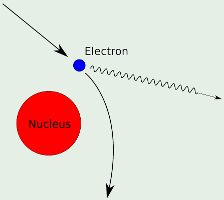
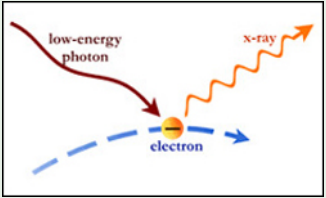


Fig. 2. Energy dependence of nuclear enhancement factor contributions from each ISM component.

Cross sections – Bremsstrahlung and IC

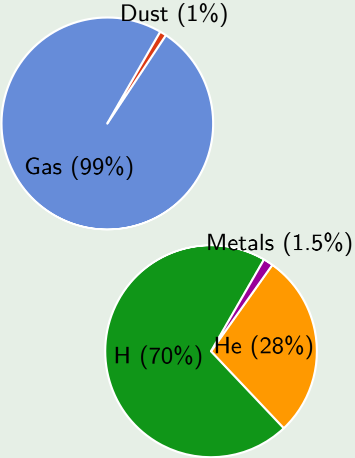




- Bremsstrahlung has been accurately calculated (Appendix A of Strong et al. 2000, ApJ, 537, 763)
  - Important to differentiate between neutral and ionized interstellar gas.
- IC cross section also well established (Jones, 1968, Phys Rev, 167,1159)
  - Depends on incidence angle between photon and electron
  - Anisotropy of ISRF can change emission by several tens of percent

Interstellar matter

Components by mass

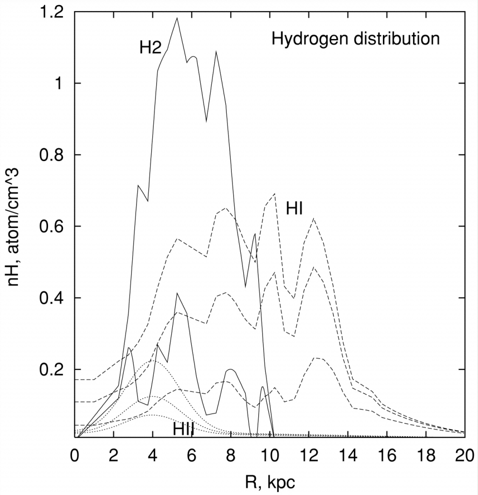


- Often referred to as the ISM and accounts for $\sim 10\%$ of the mass of the Galactic disk.
- Split into dust and gas phase with a gas-to-dust ratio of ~ 100.
- The gas phase consist of mostly hydrogen and helium and is split into components depending on temperature and ionization (Ferriere 2001)

Component	T [K]	n [cm^3]	M [$10^9 M_\odot$]
Cold molecular	10–20	10^2–10^6	1.3 – 2.5
Cold atomic	50–100	20–50	}6.0
Warm atomic	6000–10000	0.2–0.5	
Warm ionized	~ 8000	0.2–0.5	1.6
Hot ionized	$\sim 10^6$	~ 0.006	

The three components of interstellar gas

Distribution of Hydrogen



Moskalenko et al. 2002, ApJ 565

- Atomic hydrogen (H I): The most massive phase with a large filling factor and a scale height of about 200 pc at the solar location.
- Molecular hydrogen (H_2): The densest phase and very clumpy with a scale height of about 100 pc at the solar location.
- Ionized hydrogen (H II): The least significant component with a large scale height. Also clustered around massive star forming regions, so called H II-regions.
- Helium is the fourth component, assumed to exactly trace the density of hydrogen.

Atomic hydrogen — The 21-cm line emission

- Interactions between the magnetic moment of the proton and electron in the hydrogen atom results in hyperfine splitting of the lowest state.
- The energy of the line is 5.9 μeV and the spontaneous transition probability $3 \cdot 10^{-15}$ s^{-1} so the excitations are collisionally dominated in most of the ISM.
- We define the excitation temperature T_S using the Boltzmann equation

$$\frac{n_2}{n_1} = \frac{g_2}{g_1} e^{-E/kT_S}$$

  where n_2/n_1 is the ratio between the number of atoms in the different states, $g_2/g_1 = 3/1$ is the statistical weights of the states, E is the energy difference between the states and k is Boltzmann's constant.
- T_S is often called spin temperature and it is related to the kinetic temperature of the gas.

Radiative transfer

- Need to solve the radiative transfer equation

$$\frac{dT_B(\nu)}{d\tau(\nu)} = T_S(s) - T_B(\nu)$$

where τ is the opacity and

$$T_B(\nu) = \frac{2\nu^2 k I(\nu)}{c^2}$$

is the brightness temperature that is related to the specific intensity $I(\nu)$.

- In the case of large optical depth $T_B = T_S$ as expected from thermal equilibrium.
- Solving the equation is non-trivial because both $\tau(s)$ and $T_S(s)$.
- In the special case of homogeneous H I medium, the solution is

$$T_B(\nu) = T_{bg}(\nu)e^{-\tau(\nu)} + T_S\left(1 - e^{-\tau(\nu)}\right)$$

where T_{bg} is background radiation, usually the CMB.

Radiative transfer

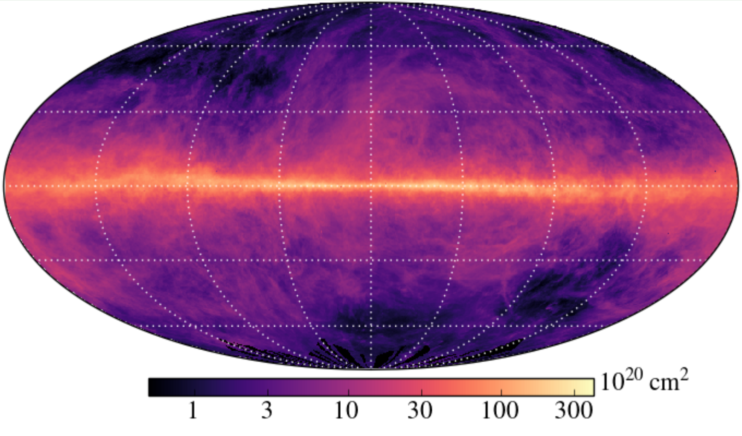
- Due to motion of the H I gas, the line emission is Doppler shifted. Very common to use the Doppler velocity v instead of ν in the equations.
- The optical depth can be related to column density through

$$\tau(v) = N_{HI}(v)\sigma = \frac{N_{HI}(v)}{CT_S}$$

  where we have used that the total cross section is $\sigma = 1/(CT_S)$ with $C = 1.83 \cdot 10^{18}\ \mathrm{cm}^{-2}\ \mathrm{K}^{-1}\ (\mathrm{km/s})^{-1}$.
- Two limiting cases:
  - $\tau \ll 1$: In this case $T_B(v) = (T_S - T_{bg})\tau(v) \approx T_S\tau(v) = N_{HI}(v)/C$ and the brightness temperature is proportional to the column density.
  - $\tau \gg 1$: In this case $T_B(v) = T_S$ and the brightness is independent of the column density.
- Reality is in between and T_S generally not constant within a single velocity bin.
- Almost all analysis assume a single T_S for the entire Galaxy, often a very large value

Observations of the 21-cm line

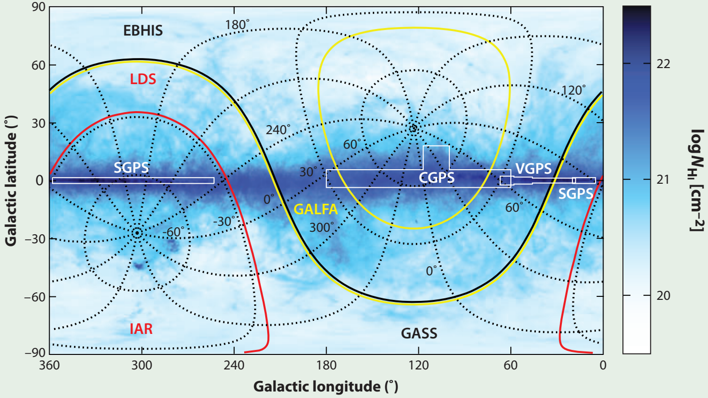
HI4PI observations (Bekhti, N. et al. 2016)



- The most recent full-sky dataset is the HI4PI (GASS+EBHIS) survey (Bekhti, N. et al. 2016) with an angular resolution of 16 arcmin and 1.4 km/s velocity resolution.

Other surveys

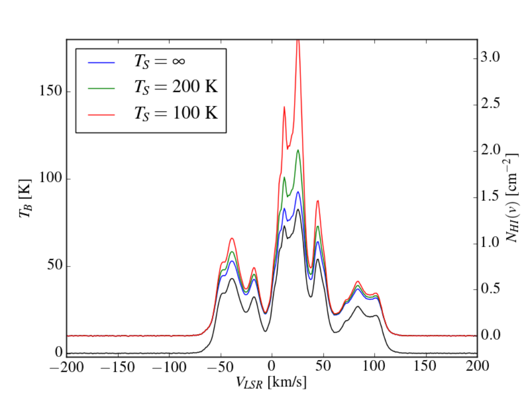
Outline of surveys (Kalberla & Kerp 2009)



- Several high resolution surveys have been done in the Galactic plane as part of the International Galactic Plane Survey (IGPS) `http://www.ras.ucalgary.ca/IGPS/`
- Arecibo also provides high resolution surveys along its field of view.

Effects of T_S

Density for various T_S



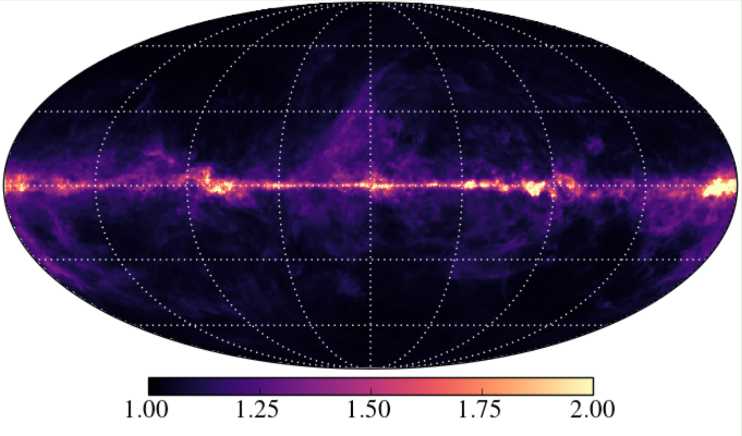
- All of the figures above have used the optically thin assumption with $T_S \gg T_B$.
- Accounting for finite values of T_S results in the equation

$$N_{HI}(v) = -CT_S \log\left(1 - \frac{T_B}{T_S - T_{bg}}\right).$$

- As $T_S \to T_B + T_{bg}$ we have $N_{HI}(v) \to \infty$.
- Getting the value of T_S correct can have a significant impact on the derived column density.

Effect of T_S

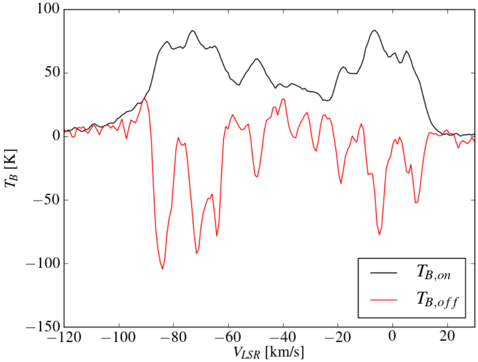
Ratio map



- The effect is not uniform across the sky.
- Map shows ratio between N_{HI} derived for $T_S = 125$ K and optically thin assumption.

H I in absorption

Example on/off spectrum



Strasser et al. 2004.

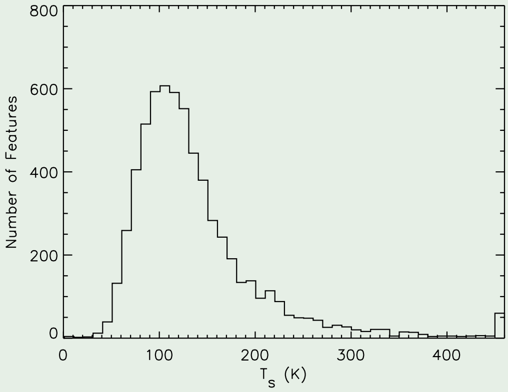
- We can re-write the radiative transport equation as

$$T_B(v) = (T_S - T_{bg})\left(1 - e^{-\tau(v)}\right) + T_{bg}$$

  and observations are usually given as $T_B(v) - T_{bg}$.
- If $T_{bg} > T_S$ we will see absorption of the background emission rather than emission from H I.
  - This can easily happen if there are bright radio sources in the background.
  - Nearby observations can be used to estimate the effect of the narrow source.

H I in absorption, determining T_S

Distribution of T_S values



From Strasser & Taylor 2004.

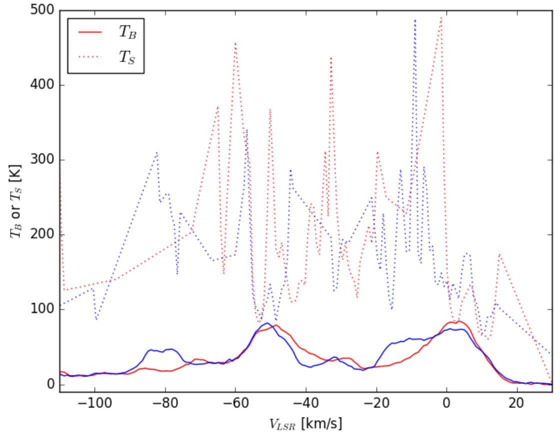
- Assuming that T_S and τ varies slowly over the Galaxy, we can use the on/off technique to estimate τ and T_S

$$T_{B,on}(v) - T_{B,off}(v) = (T_{source} - T_{bg})e^{-\tau(v)}$$

  where we estimate T_{source} and T_{bg} from radio continuum emission.
- Derived values of T_S range from few 10s K up to several thousand K.
  - In good agreement with the value of T_S being close to T_k for the cold neutral medium.

Example of nearby sightlines

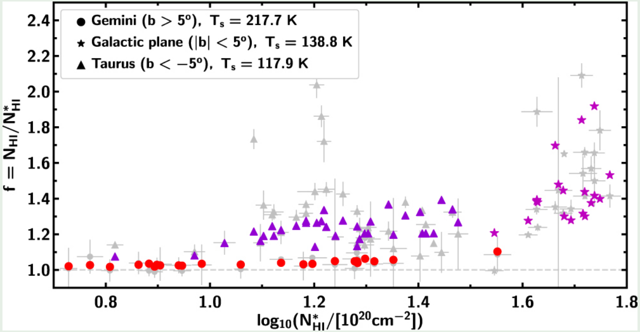
Two nearby sightlines



- The following plots shows T_B and T_S for two sightlines with less than half a degree separation. (Data from Strasser & Taylor 2004)
- Clear and significant discrepancy around -50 km/s and 0 km/s.
- Global fixed value of T_S not appropriate and neither are interpolation between observations.

Systematic study

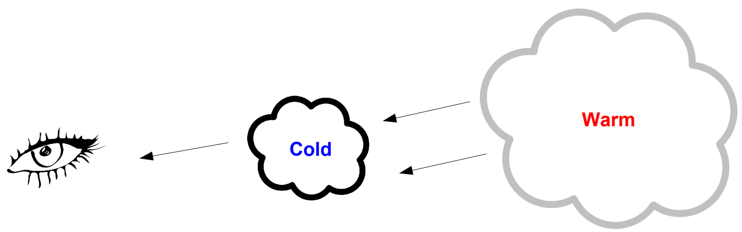
N_{HI}/N_{HI}^{*} for isothermal T_S and accurate



Ngyuen et al. (2019) ApJ 880

- Comparing isothermal T_S correction and one using accurate T_S results in reasonable estimates.
  - Better for low column density.
  - Requires specialized T_S values for each region.
  - Worse in regions near molecular clouds.
- Easily off by 50% or more for individual sightlines.

H I self absorption (HISA)



- Cold gas can absorb emission from warmer background causing a twofold effect
  - Emission from the warm background is reduced
  - Emission from the cold foreground is missing
- Usually narrow features in velocity and space that are difficult to detect.
- Affects about 5% of spectral bins in dedicated high-resolution surveys.

Molecular hydrogen – observations of H_2

- No permanent dipole moment and lowest energy transitions with energy levels $E/k \approx 500$ K above ground.
  - No emission from could H_2 gas, it can only be seen in absorption.
  - Need a tracer for H_2 gas.
- The CO molecule is the most favored tracer for several reasons:
  - Its $J < 4$ rotational transitions are low energy, being between 5 and 22 K above ground level.
  - In high density molecular regions, C is nearly depleted into CO molecules and the $J = 1 - 0$ transition is optically thick.
  - CO forms and destructs under similar conditions as H_2, although it requires more column density before becoming fully molecular.
- Other tracers, such as OH and C$+$ can also be used.

Tracing H_2 column density with CO

- It has been observationally shown that integrated ^{12}CO $J = 1 - 0$ line intensity (or brightness temperature) is approximately linearly related to H_2 column density

$$N_{H_2}(v) = X_{CO} W_{CO}(v) = X_{CO} \int dv T_{B,CO}$$

- This relationship has been confirmed with several observations:
  - Virial mass estimates.
  - Optically thin emission from ^{13}CO and ^{18}CO.
  - Comparison with dust extinction and emission.
  - Interstellar γ-ray emission.
- $X_{CO} \sim 2 \cdot 10^{20}$ cm^{-2} (K km/s)$^{-1}$ in the Milky Way.

Why is the ^{12}CO $J = 1 - 0$ line a good tracer?

- The molecular gas is optically thick to the ^{12}CO $J = 1 - 0$ line emission and observed brightness is independent of column density.
  - Why then does the integrated line correlate with column density?
- Bolatto, Wolfire & Leroy (2013) give a great overview; basically the line width of a molecular cloud is correlated with its size which is again correlated with the mass.
  - This has to do with turbulence in the interstellar medium and how turbulence in molecular clouds is related to its size.
  - The line width is determined by turbulence rather than thermal motion.
- The result is that the column density is roughly linearly related to the integrated line intensity.
  - Even in the best scenarios, X_{CO} is dependent on both the density and temperature of the molecular cloud.

Why is the ^{12}CO $J = 1 - 0$ line a bad tracer?

- While currently being the best we have, the ^{12}CO $J = 1 - 0$ line is not a perfect tracer for H_2 column density.
- In medium density regions at the periphery of molecular clouds, H_2/CO ratio varies rapidly due to photo dissociation of CO.
  - This results in so-called dark neutral medium; regions where column density of H_2 is underestimated by CO observations.
  - More on that later.
- The gas can become optically thin to the line emission in case of large turbulence or otherwise large velocity dispersion.
  - In this case the X_{CO} value is expected to be an order of magnitude smaller, about $2 \cdot 10^{19}$ cm^{-2} (K km/s)$^{-1}$
  - Tidal distortion of clouds near the Galactic center are a good example of this.

Observations of CO

From Heyer & Dame (2015)

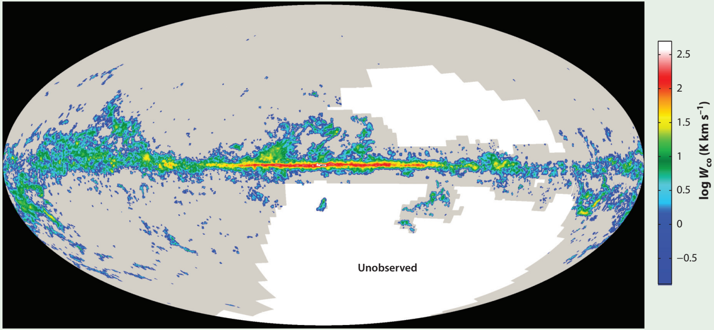


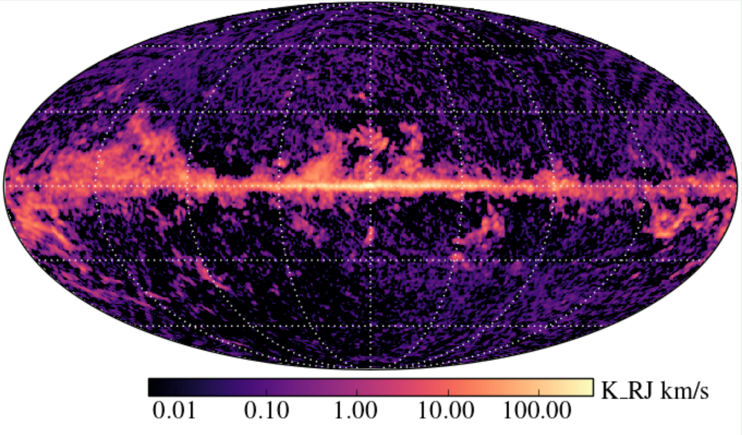
Figure 3

An image of ^{12}CO $J = 1$–0 emission constructed from the recent Center for Astrophysics campaign to examine the high-latitude sky and the composite surveys of Dame et al. (2001) and Mizuno & Fukui (2004).

- The largest resolved CO line emission is the composite survey by Dame et al. (2001) which covers the entire Galactic plane and most high latitude emission.

Observations of CO

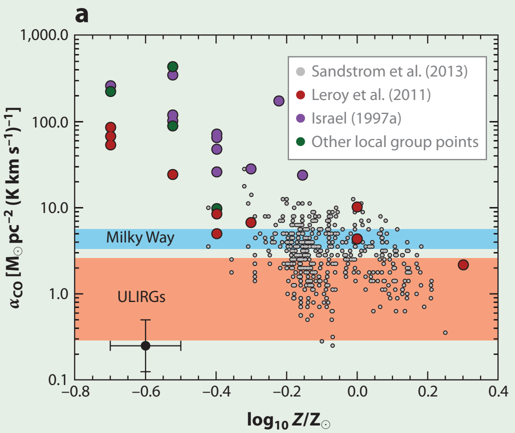
Planck observations



- The Planck satellite provides full sky integrated CO $J = 1 - 0$ emission but there is some contamination from other components because they lack the spectral resolution to resolve the line.

X_{CO} dependence on metallicity

Bolatto et al. (2013)

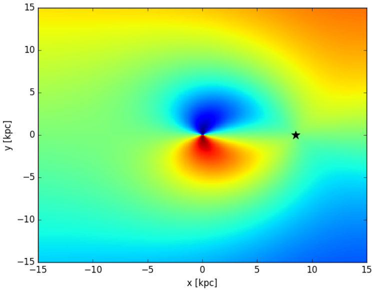


- H_2/CO ratio should depend on the metallicity of the molecular clouds.
- There are several effects in play:
  - The ratio of C atoms obviously depends on metallicity.
  - The dust properties that provide much of the shielding for photo dissociation also depend on metallicity.
  - Finally the properties of the stellar distribution providing the UV radiation field are metallicity dependent.

Kinematic distances

V_{LSR} in the Galactic Plane

Figure showing V_{LSR} in the Galactic plane for $\Theta(R) = \Theta(R_\odot)$.



Lines of sight with $\sin l \approx 0$ provide no distance information.

- A key benefit of line emission gas tracers over others such as dust and γ-rays is the usage of Doppler shift as distance estimation.
- Under the assumption that the gas is in spherical rotation around the Galactic center we can easily turn velocity into distance

$$V_{LSR} = \sin l \cos b \left[\frac{R_\odot}{R} \Theta(R) - \Theta(R_\odot) \right]$$

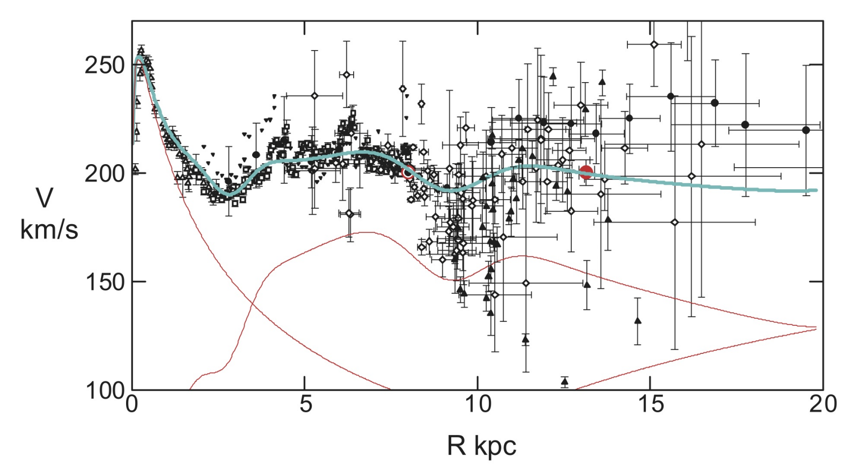
  where $\Theta(R)$ is the Galactic rotation curve, $R_\odot$ is the radius of the sun and l and b are Galactic longitude and latitude, respectively.
- V_{LSR} is the velocity measured with respect to the local standard of rest that is moving in a circular orbit around the Galactic center.

The rotation curve

- Several different methods used depending on the radius:
  - Inner Galaxy: The largest V_{LSR} velocity is achieved at the tangent location where $R = R_{\odot} \sin l$. This can be identified in the emission surveys as the emission at highest velocities.
    - Turbulent and peculiar motion can make this point difficult to identify.
  - Around the Sun: parallax distances to H II regions, planetary nebulae and stars are used to measure the radius.
    - Affected by peculiar motions that can vary throughout the Galaxy
  - Outer Galaxy: Assume scale height of H I varies with radii only.
    - There is evidence (e.g. Levine et al. 2006) that the scale height is azimuth dependent.
- All methods depend on assumption about location and velocity of the Sun.

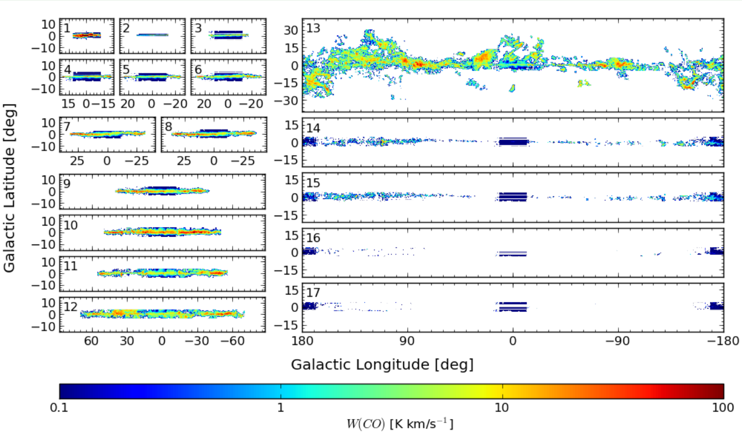
The rotation curve

Combination of several different approaches (Sofue et al. 2009)



Annular distribution of CO

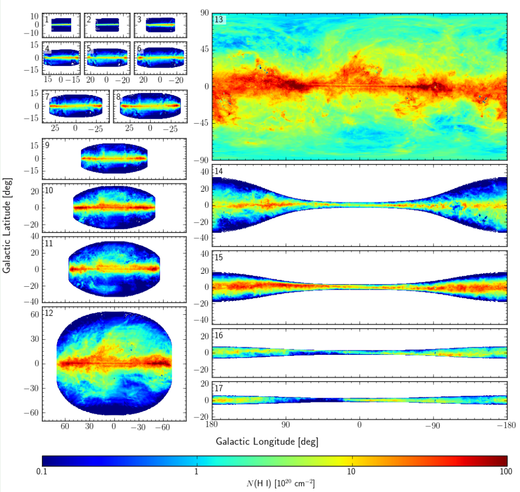
Ackermann et al. 2012



- Using the rotation curve of Clemens (1985), the Dame et al. (2001) CO survey and the LAB H I survey can be turned into annular maps.
- Figure from Ackermann, M. et al. 2012, ApJ, 750, 3.

Annular distribution of H I

Ackermann et al. 2012



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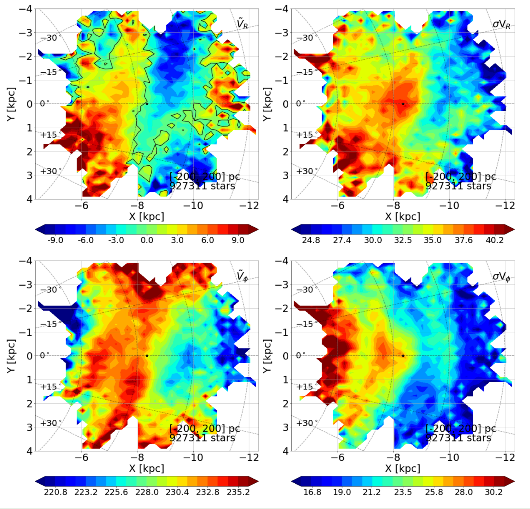
Results from GAIA

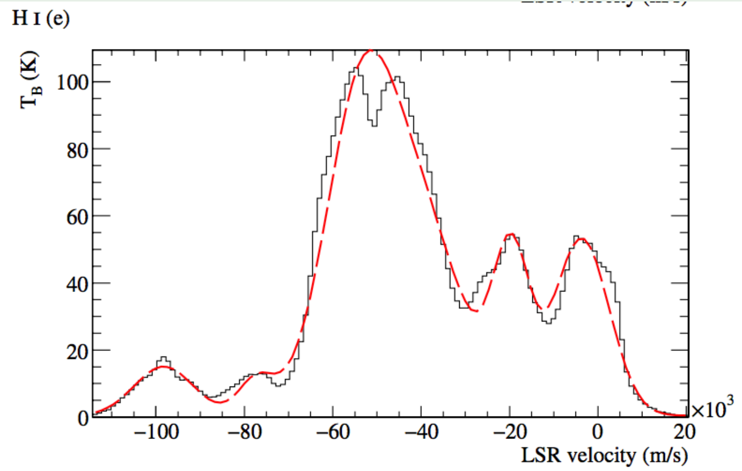
Katz et al. 2018, A&A, 616, 11



- GAIA has measured parallax distances and proper motions of millions of stars.
- Can be used to reconstruct the velocity field of the Galaxy around the Sun.
- Clear deviations from cylindrical rotation and considerable dispersion

Accounting for thermal and turbulent motion

Abdo et al. 2018, ApJ, 710, 133



- The line emission is spread because of thermal and turbulent motion of gas in the ISM.
- Split the line emission into components by fitting it with a set of Gaussian functions.
- Assign gas according to components rather than bin-by-bin.

Dust as an estimator of total gas column

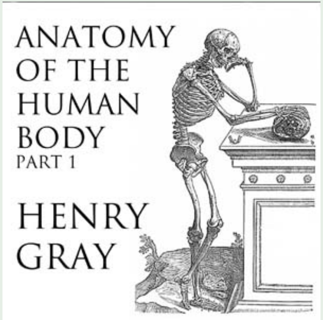
From the internet

"Sure it's beautiful, but I can't help thinking about all that interstellar dust out there."

- Depending on formation, dust should be well mixed with gas
- Observations of dust column should therefore correlate with gas column
- Two methods for estimating dust: Emission (IR) and absorption (Stars)
  - Emission has good and uniform coverage, but suffers from temperature dependency
  - Absorption is nearly independent of temperature, but coverage is less uniform
- Absorption measurements can be used to extract distance information.

Dust in emission

Gray body



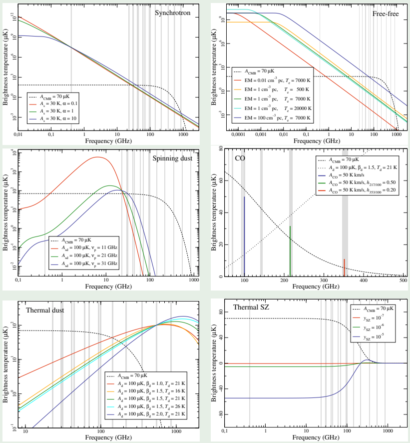
- Intensity of the emission is strongly temperature dependent, variation in dust temperatures from 16 K to 20 K give rise to factor 5 difference in intensity for the same dust column.
  - We need to measure the dust temperature to get a good handle on the dust column.
- Dust is usually modelled as a gray body

$$I(\nu) = A_d \left(\frac{\nu}{\nu_0}\right)^{\beta_d+1} \frac{e^{h\nu_0/(kT_d)} - 1}{e^{h\nu/(kT_d)} - 1}$$

where ν_0 is fixed and A_d, T_d, and β_d are fit parameters.

Dust observations

Data from Planck

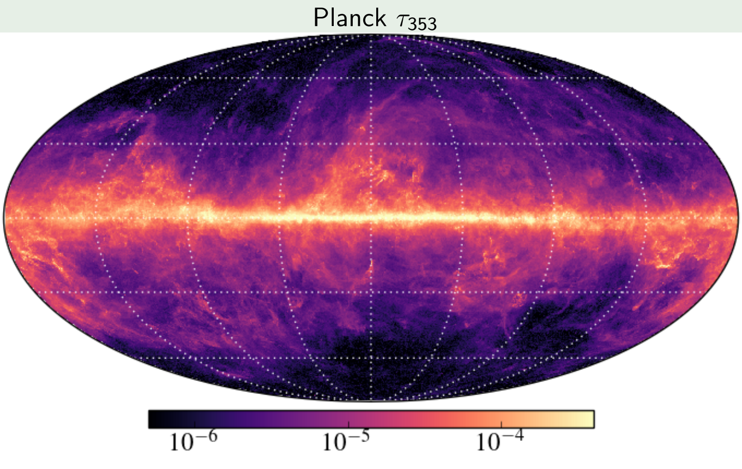


- Planck satellite observes in 9-bands from 30 GHz to 857 GHz.
- Several emission mechanism known in the frequency range: synchrotron, free-free, CMB, spinning dust, and CO emission lines.
- Not as simple to analyse as line emission.
  - Requires fitting of components in each direction.

Extracting dust properties

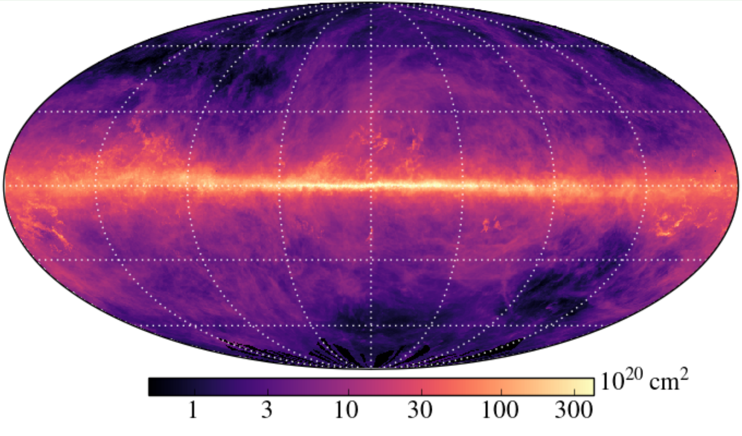
- Two methods can be used to convert the gray body model to dust column density:
  - Radiance: $\int I(\nu)d\nu \propto U\bar{\sigma}N_d$
  - Opacity: $\tau_{\nu_0} = I(\nu_0)/B_\nu(\nu_0) = \sigma_{\nu_0}N_d$
  - U is stellar emission and σ dust cross section
- Assuming $N_d \propto N_H$ gives us two estimates for the total column density of gas.
- Adding information in shorter wavebands by IRAS improves the constraint and it is easier to extract physical properties of the dust.

Correlation with H I



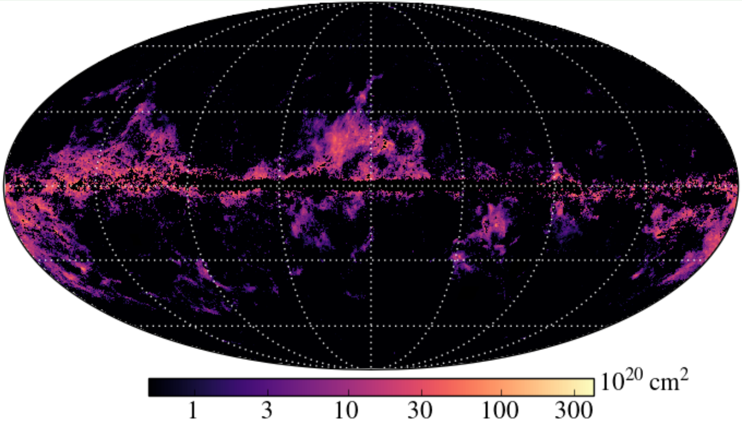
Correlation with H I

HI4PI + Dame



Subtracting gas from dust

The dark neutral medium (DNM)



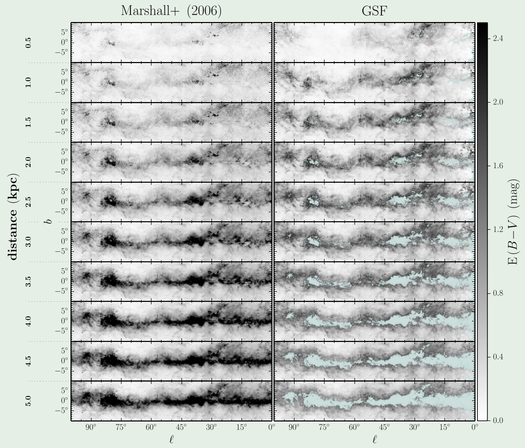
- Linear fit of H I and CO to E(B-V) dust map from Schlegel et al. 1998.

$$E(B-V) = \sum_r a_r N_{HI,r} + \sum_r b_r W_{CO,r}$$

- The map shows the residual emission

Dust in absorption

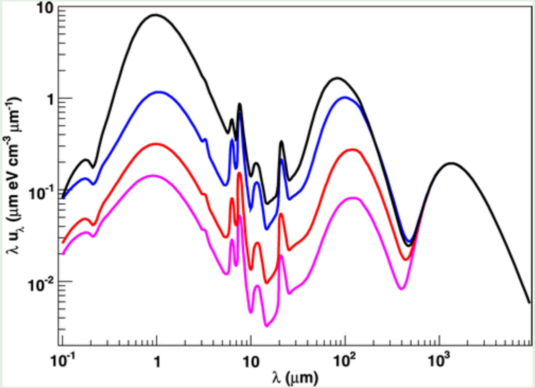
Green et al. 2015, ApJ, 810, 25



- Because absorption measurements only measure dust columns between the observer and source, we can also get distance information.
- By observing absorption from many stars along closely aligned lines of sight we can build an absorption profile and group the stars in distance bins.
- This results in a 3D map of dust absorption.
- Method starts to break down far away and in highly absorbed regions.

The Interstellar Radiation Field (ISRF)

Porter et al. 2008, ApJ 682



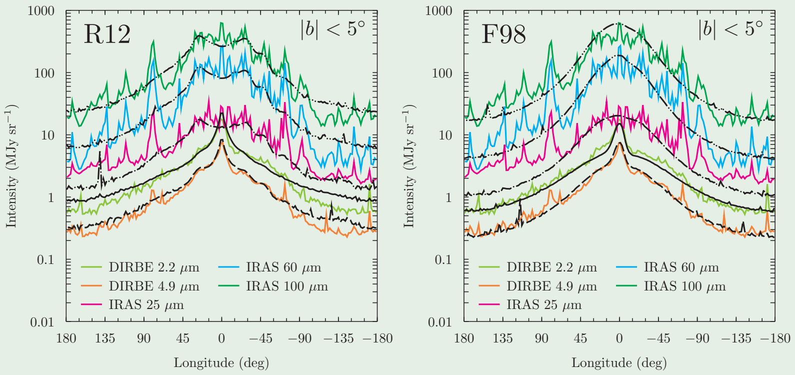
- Three main components:
  - Stellar light.
  - Dust re-emission of stellar light.
  - The cosmic microwave background.
- Only directly observable from our position $\Rightarrow$ Need modeling codes to predict its distribution.
  - Stellar distribution and properties.
  - Dust distribution and properties.
  - Radiative transport.

The Interstellar Radiation Field (ISRF)

- The interstellar medium is not transparent to stellar light
  - Requires calculating the radiative transport taking into account details of the Milky Way.
- Spatial distribution of dust can be estimated from gas.
- Dust composition also important as it affects absorption/emission properties.
- Inverse Compton (IC) cross section is angle dependent so we need angular dependent SEDs throughout the Galaxy.
  - A skymap of SEDs at each grid point.
- Significant freedom in model properties, especially in the inner Galaxy.
- Following examples calculated by means of full radiation transfer modelling using FRaNKIE code.

3D Interstellar radiation field (ISRF)

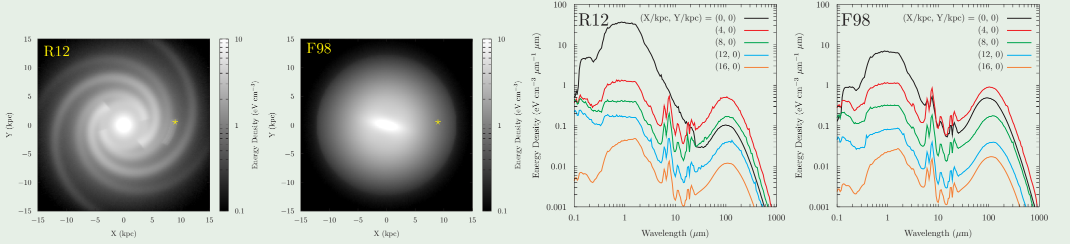
Porter et al. ApJ 846, 67 (2017)



- R12 includes stellar disc, ring, bulge, 4/2 major/minor arms + dust disc with inner hole toward GC.
- F98 includes 'old' and 'young' stellar discs that are warped, spheroidal bar, and warped dust disc with inner hole toward GC.

3D ISRF in the plane

Porter et al. ApJ 846, 67 (2017)



- Different integrated energy density distributions that reflect the stellar and dust distributions.
- In and about the inner Galaxy there is a factor ~ 5 difference between the models.

Estimating the CR flux – two main methods

Template method

- Uses templates for the target properties and determines the CR distribution from a fit to γ-ray data
- Does not depend on source properties and propagation.
- Fast method, no need to solve complex propagation equations.
- Generally gives a better representation of data.

Propagation method

- Assumes CR source properties and propagation parameters to determine the CR distribution solving the propagation equation.
- Not biased by unmodeled components.
- Smoothly varying CR distribution.
- Self-consistent IC emission.

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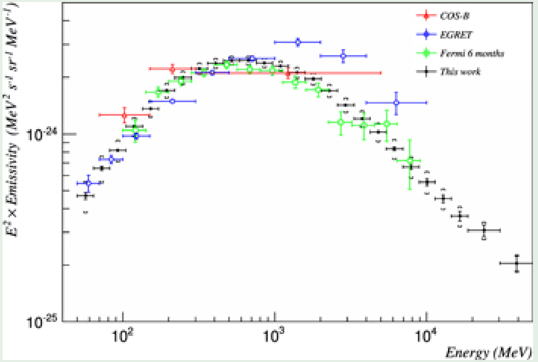
Potential merger solution

Create templates using propagation codes and fit them to data. Feed fit results to propagation code and iterate.

High latitudes, local neighborhood

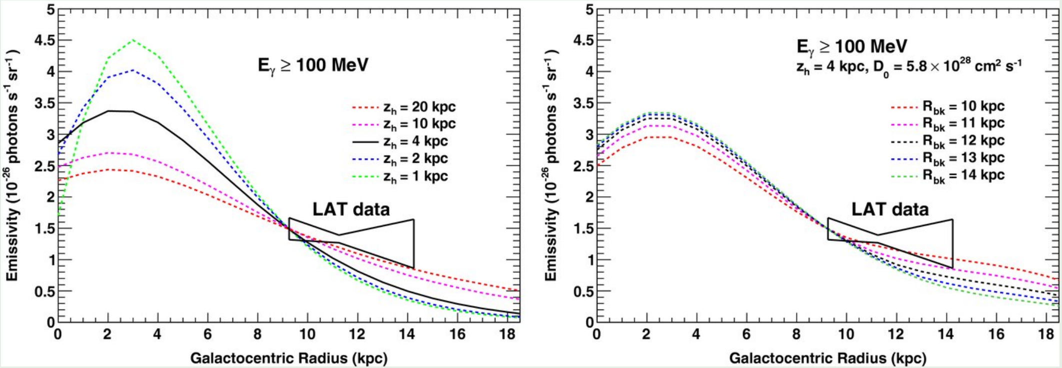
Casandjian, J. M. 2015, ApJ, 806,2



- Several analysis have been performed using the template method for nearby regions.
  - Most focused on nearby molecular clouds
- H I template used to extract the emissivity ($F_c\sigma_{c\rightarrow\gamma}$) as a function of energy.
- Most significant results
  1. Emissivity spectrum compatible with local observations of CR.
  2. Nuclear enhancement factor is important.
  3. Significant contribution from the DNM around molecular clouds.

Outer Galaxy

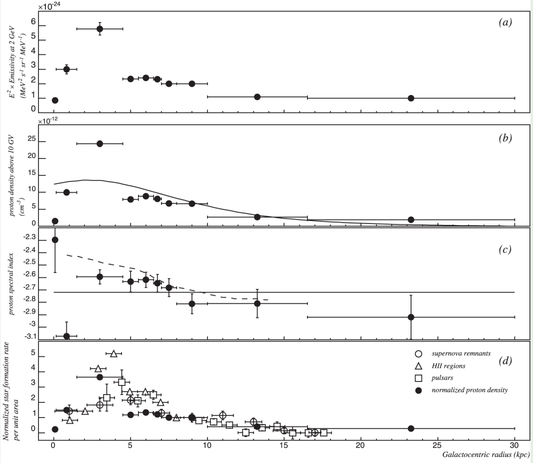
Ackermann et al. 2010, ApJ, 726,2



- Splitting the gas templates into radial bins allows the determination of the CR gradient.
- Comparison with GALPROP models reveal more emission than predicted.

Inner Galaxy

Acero et al. 2015, ApJS, 223,2



- Evidence for CR spectral hardening towards the inner Galaxy.
- Depends on the underlying distribution of the IC model
  - Ajello et al. 2016, ApJ, 819,1 shows that the hardening depends on the details of the templates.
  - Significant uncertainty in the spatial distribution of the IC emission.
- Selig et al. (2015, A&A, 581, 126) also found hardening using non-templated analysis.
  - Their method cannot separate gas from IC, so difficult to assign one to the other.

GALPROP code for CR transport and diffuse emission

- Tool for modelling and interpreting CR and non-thermal emissions data for Milky Way and other galaxies in a self consistent and realistic way.
- GALPROP can be downloaded/installed locally, or run from a web-browser at the GALPROP website: `http://galprop.stanford.edu`
- Recently released v56 includes among other things
  - Spatial variation in diffusion coefficient and Alfvén speed (re-acceleration).
  - Generalized source distributions (2D and 3D) and spectral models.
  - 3D gas and ISRF models.
  - Improved solvers for propagation – dramatic performance increase.
  - New integrators for non-thermal intensity map calculations.

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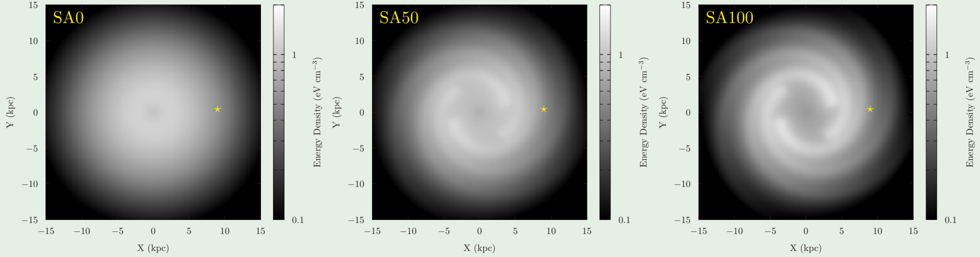
A little warning

- Note that there is no such thing as "the" GALPROP model.

3D models for interstellar emission

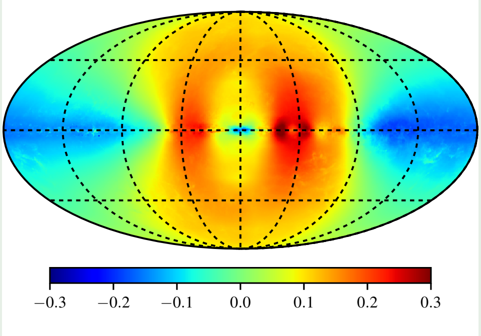
Porter et al. 2017, Johannesson et al. 2018

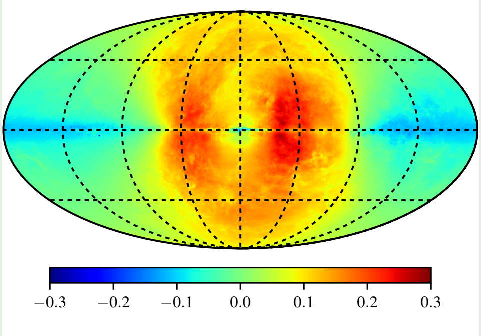


- GALPROP v56 + 3D ISRF + 3D gas + 3D CR source density.
- 3 CR source density models: CR power injected according to 'Pulsars' (2D), 50% Pulsars + 50% spiral arms, 100% spiral arms.
- Propagation parameters adjusted for each to reproduce measurements of CRs near Earth. Not tuned to γ-ray data.

Interstellar Emission for SA100 + R12 + 2D gas

Fractional residual maps (model/2D reference - 1) at 10 MeV (left) and 1 GeV (right)





- Most of the enhancement in the IC component. Squared effect because spiral arms of CR sources and ISRF align.

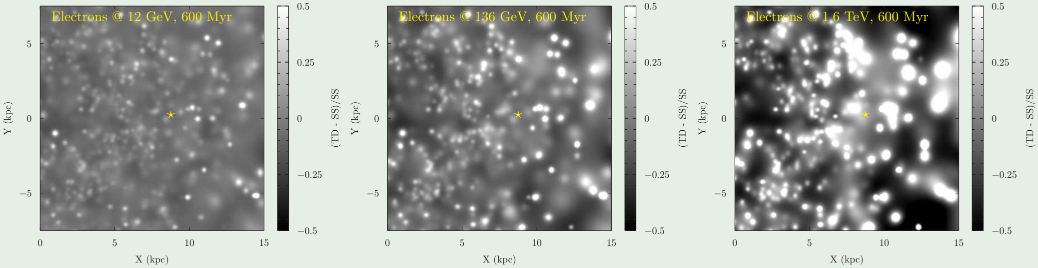
Recent developments – Time dependent calculations

Porter et al. 2019, ApJ accepted arXiv/1909.02223

- CRs are most likely generated in individual sources over short periods of time and not continuously from a smooth distribution.
- Transition from a smooth "sea" of old propagated CRs to distribution of freshly accelerated sources caused by energy losses.
- Most notable in IC emission at $\gtrsim 100$ GeV energies.
  - Lots of photons collected by *Fermi*-LAT; HESS Galactic plane survey; HAWC; CTA in the near future.
  - Very important to have a tool that can explore these features.
- GALPROP now efficiently calculates full 3D interstellar emissions using time dependent CR injection and/or propagation.
- Implemented a discrete sampler that can use arbitray underlying source density. Number of sources, their duration, and their size are user defined parameters.
- Also allows for non-linear grid spacing to improve resolution where needed.

Time dependent CR source distribution

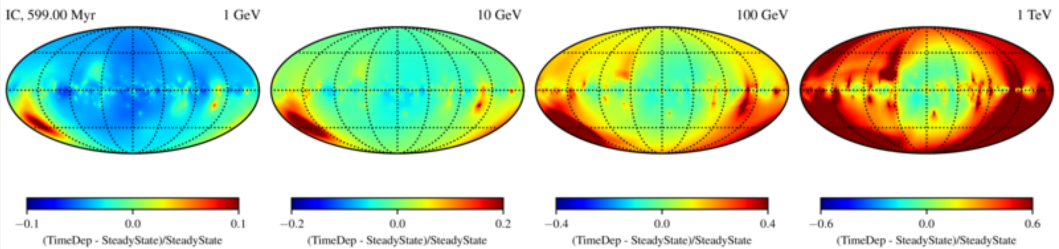
Fractional residuals compared to steady state at 10, 100, and 1000 GeV



- SA50 source density, propagation parameters determined from calculations using smooth distribution. Same average CR injected power.
- Sources are 50 pc wide and are on with constant power for 100 kyr.

Fractional Residual Movies – IC

Fracional residual skymaps compared to steady state at 4 different energies



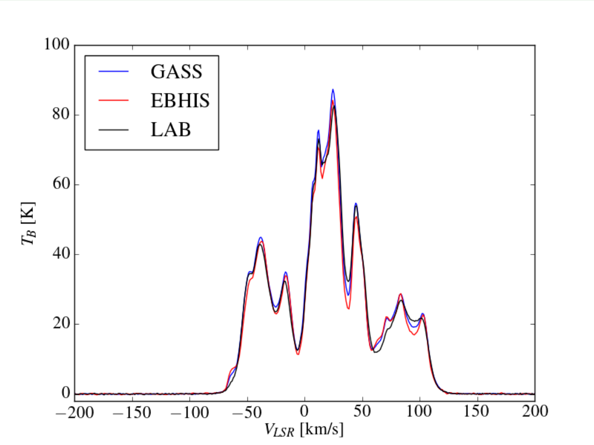
- IC emission — Time dependent - steady state / steady state.
- Energy dependent effects – strongest at the highest energies, but non-negligible over entire LAT energy range.

Thank you

Questions?

Higher resolution surveys

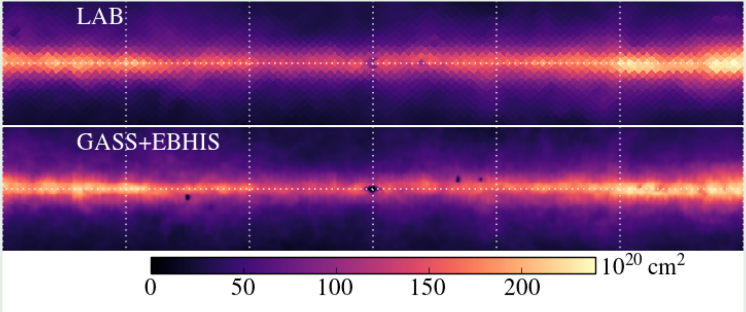
Spectrum at “identical” location



- HI4PI replaces the lower resolution LAB survey. Observations have changed in overlapping regions.

Higher resolution surveys

Galactic plane



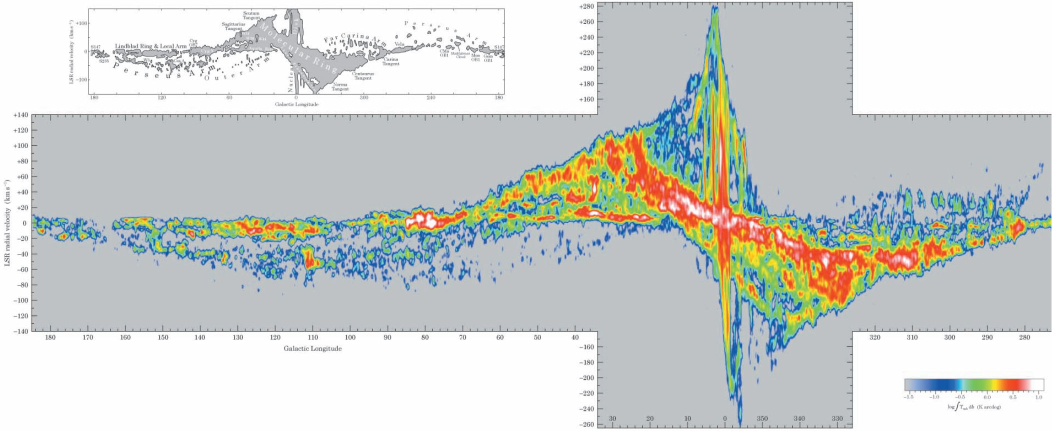
- Higher resolution also enables better identification and removal of bright background point sources.

Interstellar dust

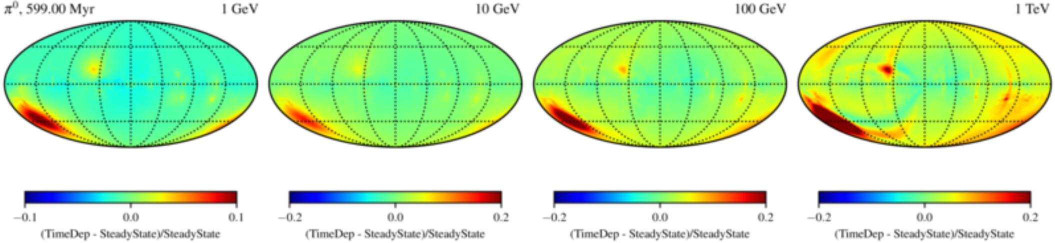
- Contains most of the heavy metals of the cold interstellar medium.
- Sky distribution closely correlated with that of hydrogen column density.
- Exact chemical composition and grain size distribution uncertain.
  - Graphite, silicate and polycyclic aromatic hydrocarbon (PAH) grains have been identified
  - Power-law size distribution with an index of ~ -3 works well to explain observations.
- Is not important as a target but is a crucial component in the dynamics of the interstellar matter.
  - Efficiently scatters and absorbs radiation.
  - The breeding ground for molecules.
- Identified through absorption of stellar light and thermal infrared emission with temperature in the range of 15 to 20 K.

CO longitude velocity diagram

- Velocity information provides information on the large scale structure of the Galaxy.



Fractional Residual Movies – π^0-decay



- π^0-decay emission — Time dependent - steady state / steady state.
- Effect not as large as for IC, but still significant.

Time dependence – Summary

- Even though source on time is a lot smaller than CR residence time, the resulting calculations show a significant deviation from steady state calculations for both protons and electrons.
- Fluctutations in interstellar emission of the order of 10% at 1 GeV, up to 60% at 1 TeV for IC emission.
- Difficult to look for faint DM signal in all that noise.
- Must know the CR source history to make accurate predictions – revert to statistics otherwise.