Cosmic IR Background
&
COBE, Spitzer and WISE
by
Ned Wright (UCLA)

http://www.astro.ucla.edu/~wright/intro.html

See:

• http://www.astro.ucla.edu/~wright/cosmolog.htm
• http://www.astro.ucla.edu/~wright/DIRBE
• http://www.astro.ucla.edu/~wright/CIBR
• http://spitzer.caltech.edu
• http://wise.astro.ucla.edu
• $I_\nu$ - specific intensity, energy per
  (area $\times$ time $\times$ frequency $\times$ solid angle).
  $10^{-20}$ W/m$^2$/Hz/sr = 1 MegaJansky/sr [MJy/sr].
• $I = \int I_\nu d\nu$ - bolometric intensity, energy per
  (area $\times$ time $\times$ solid angle).
  1 nW/m$^2$/sr.
• $\nu I_\nu$ - intensity per octave, energy per
  (area $\times$ time $\times$ logarithmic bandwidth $\times$ solid angle).
  1 nW/m$^2$/sr.
• $J_\nu = (4\pi)^{-1} \int I_\nu d\Omega$: mean intensity – the angle averaged
  intensity.
• $F_\nu = \int I_\nu \cos \theta d\Omega$: monochromatic flux, energy per
  (area $\times$ time $\times$ frequency).
  $10^{-20}$ W/m$^2$/Hz = 1 MegaJansky [MJy].
Wide window on the CBR
Backgrounds

• Microwave – the CMB is 10,000 times brighter than the galactic foreground & the spectrum is very close to a blackbody
• Far Infrared – the FIRB is 10 times fainter than the galaxy with a spectrum similar to the galaxy
• Near IR and Optical – also 10 times fainter than galaxy
• X-ray – the XRB is 10 times brighter than the galaxy
In a homogeneous unchanging Universe every line of sight will end on a star. So why is the night sky not as bright as the surface of a star? The Cosmic Infrared Background is what remains after this Olbers’ paradox is resolved.
Sources of the CIRB
Expanding Mirrored Box

- The Universe is *homogeneous* & *isotropic*.
- Reflections in a mirrored box look like the Universe.
- Expanding mirrored box gives a redshift with $\lambda \propto a(t)$. 
Consider a mirrored box, where the mirrors move with the galaxies in the Hubble flow, and define the *comoving luminosity density*:

\[
\ell(t) = \frac{\sum_{\text{in box}} L_{\text{gal}}(t)}{V_{\text{box}}(t_\odot)}
\]

For a static, unchanging Universe the energy density in the box now is

\[
u(t_\odot) = \frac{4\pi J}{c} = \int_{-\infty}^{t_\odot} \ell(t_\odot) \, dt \rightarrow \infty \quad \text{[Olber's Paradox]}
\]

In an expanding Universe with scale factor \( a(t) \), and \( 1 + z = a(t_\odot)/a(t) \), then:

\[
u(t_\odot) = \frac{4\pi J}{c} = \int_0^{t_\odot} \frac{\ell(t)}{1 + z} \, dt
\]
The total energy produced, $\int \ell(t) dt$, is more than the CIRB energy density because it does not have the $(1 + z)$ factor in the denominator. For the baryon density given by Big Bang Nucleosynthesis, $\Omega_B h^2 = 0.02$, if 1% of the baryons are converted from hydrogen to helium releasing 0.7% of their mass into energy, then

$$\int \ell(t) dt = 0.02 \times 0.01 \times 0.007 \times 10539.4 \frac{\text{eV}}{\text{cm}^3} = \frac{1}{68} \frac{\text{eV}}{\text{cm}^3}$$

$c/[4\pi]$ times this energy density is $56 \text{ nW/m}^2/\text{sr}$. 
The relationship between time and redshift is

\[ t = \frac{2}{3H_\circ(1 + z)^{1.5}} \quad \text{so} \quad \frac{dt}{dz} = \frac{-1}{H_\circ(1 + z)^{2.5}} \]

for the Einstein-de Sitter Universe with \( \Omega = 1 \), and the Hubble constant is \( H_\circ = (2/3)/t_\circ \).

Thus if \( \ell(t) \) is CONSTANT, the energy density of the CIRB would be

\[ u = \frac{1}{H_\circ} \int \frac{\ell(t_\circ)}{(1 + z)^{3.5}} dz = \frac{3}{5} \int \ell(t) dt = 0.6\ell(t_\circ)t_\circ \]

If \( \ell(t) \) is proportional to \( (1 + z) \), then the energy density of the CIRB would be

\[ u = \frac{1}{H_\circ} \int \frac{(1 + z)\ell(t_\circ)}{(1 + z)^{3.5}} dz = \frac{1}{3} \int \ell(t) dt = \ell(t_\circ)t_\circ \]
Luminosity density vs. redshift

\[ \varepsilon [L_\odot \, \text{Mpc}^{-3}] \]

UVO

PFI

RR

z

0 1 2 3 4 5
$L/(1+z)$ vs. time
Fluctuation Analysis

\[
\text{var}(F') = \int \left( \frac{L}{4\pi D_L(z)^2} \right)^2 (1 + z)^3 n_{CM}(z) D_A(z)^2 c dt d\Omega
\]

\[
= (4\pi)^{-2} \int \frac{n_{CM}(z) L^2}{(1 + z) D_L(z)^2} c dt d\Omega
\]

- Diverges like \(1/z_{\text{min}}\) or \((F_{\text{cut}})^{0.5}\)
- Always dominated by the brightest unmasked sources: galaxy edges, dwarf galaxies, \(z=1\) sources
- Contribution from high \(z\) highly suppressed
- Good for about 2X lower flux than catalog limit
DIRBE Beam Size

0.7°
DMR COVERAGE
ONE ORBIT,
DAY 45
DMR COVERAGE
ONE ORBIT,
DAY 135
Bump Chart: Where is the CIRB?
Note the triangles of zodiacal emission along the ecliptic on either side of the solar exclusion hole.
Extrapolation to Outside Solar system?

- Observe same spot on the sky through different amounts of interplanetary dust.

- Fit a model to the change in intensity vs. elongation (or time).
Interplanetary Dust Cloud Models

The observed intensity depends on a line-of-sight integral of an emissivity that depends on the dust density, \( n(x, y, z, t, \text{size,shape,composition}) \), a function of at least 7 variables. The data are given by \( I(\nu, l, b, t) \), a function of only 4 variables.

Simplification is needed. For a time independent solution, the density depends only on the integrals of the motion: \( E, L, \) and \( L_z \) which map into \( a, e \) and \( i \). The eccentricity has little effect on the line-of-sight integral, so assume the density is function only of \( r \) and \( i \).

Let \( n(r, i) = R_1(r)I_1(i) + R_2(r)I_2(i) + \ldots \)
Radial Density Profile

The Poynting-Robertson effect gives a torque of

\[ T = -\sigma \frac{rv_{orb}}{c^2} \frac{L}{4\pi r^2} \]

and since the angular momentum is \( L = m\sqrt{GMr} \) this gives an inward drift rate of

\[ \frac{dr}{dt} = \frac{T}{dL/dr} = -(2\pi)^{-1} \sigma \frac{L}{m c^2 r} \]

A steady state requires that

\[ \frac{\partial}{\partial r} \left( n(r) r^2 \frac{dr}{dt} \right) = 0 \]

and thus that \( n(r) \propto r^{-1} \).  

FIT gives \( r^{-1.23} \)
Dust Density vs inclination
A Circumsolar Ring of Asteroidal Dust in Resonant Lock with the Earth

Dermott et al., 1994, Nature, 369, 719
A Ring and a Trailing Clump
Still no CIRB Bump:
We want $\nu J_\nu$ at B but sit at A
Extrapolation to NO Galaxy?

- Galaxy is a *very* thin disk
- Average column density $\propto \csc |b|$
Extrapolation to $\csc|b|=0$ in Far IR
Atomic Hydrogen Map

21 cm H I emission

33.3  126.8  233.1  373.3  839.8  7057.5


<table>
<thead>
<tr>
<th>$\lambda$ [(\mu m)]</th>
<th>$\nu I_\nu$ [nW m(^{-2}) sr(^{-1})]</th>
<th>$I_\nu$ [MJy sr(^{-1})]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.25</td>
<td>&lt; 75.</td>
<td>&lt; 0.031</td>
</tr>
<tr>
<td>2.2</td>
<td>&lt; 39.</td>
<td>&lt; 0.029</td>
</tr>
<tr>
<td>3.5</td>
<td>&lt; 23.</td>
<td>&lt; 0.027</td>
</tr>
<tr>
<td>4.9</td>
<td>&lt; 41.</td>
<td>&lt; 0.067</td>
</tr>
<tr>
<td>12.</td>
<td>&lt; 468.</td>
<td>&lt; 1.87</td>
</tr>
<tr>
<td>25.</td>
<td>&lt; 504.</td>
<td>&lt; 4.2</td>
</tr>
<tr>
<td>60.</td>
<td>&lt; 75.</td>
<td>&lt; 1.5</td>
</tr>
<tr>
<td>100.</td>
<td>&lt; 38.</td>
<td>&lt; 1.27</td>
</tr>
<tr>
<td>140.</td>
<td>25.0 ± 6.9</td>
<td>1.17 ± 0.32</td>
</tr>
<tr>
<td>240.</td>
<td>13.6 ± 2.5</td>
<td>1.09 ± 0.2</td>
</tr>
</tbody>
</table>

$I_\nu \approx (1.3 \pm 0.4) \times 10^{-5}(\nu/100)^{0.64 \pm 0.12} B_\nu(18.5 \pm 1.2 \text{ K})$

Zodi Subtracted 3.5 Microns
Extrapolation to $\csc|b|=0$ at 3.5 $\mu$m
Detecting the Cosmic Infrared Background at 2.2μm with Ground Based and Space Based Observations

A dissertation submitted in partial satisfaction of the requirements for the degree
Doctor of Philosophy in Physics and Astronomy

by

Varoujan Gorjian
1998
• Generated many fake star fields, $|b| > 64^\circ$
• Properly allocated fluxes to DIRBE pixels
• Resulting model histogram
• Histogram shifted by 14.4 kJy/sr
• Actual zodi-subtracted DIRBE data
• Dashed: Euclidean

CIBR = 23.1±5.9 kJy/sr at 2.2 µm
14.4±3.7 kJy/sr at 3.5 µm
Intensity, Isotropy and Origin of the Cosmic Infrared Background

A dissertation submitted in partial satisfaction of the requirements for the degree Doctor of Philosophy in Physics

by

Louis Robert Levenson
DIRBE at L vs 2MASS at K

The diagram shows a scatter plot comparing the intensity at L from DIRBE with the intensity at K from 2MASS stars, measured in kJy/sr. Each subplot represents a different comparison point within the range of 0 to 100 for both axes. The data points are distributed along the lines, indicating a linear relationship between the two measurements.
We don’t need arc-sec resolution to subtract galactic stars. DIRBE was almost good enough.
DIRBE-2MASS vs ecliptic latitude

K-Band

$DZ(0)$ [kJy/sr] vs Ecliptic Latitude

Ecliptic Latitude

-80 -60 -40 -20 0 20 40 60 80
NO ZODI Principles

$I_{obs}(\lambda, l, b, t) = Z(\lambda, l, b, t; p) + I_c(\lambda, l, b)$

- Weak No Zodi: No restriction on $I_c$
- Strong No Zodi: $I_c(\lambda, l, b)$ independent of $(l, b)$ for $|b| > 20^\circ$ and $\lambda = 25 \ \mu m$.
- Very Strong No Zodi: $I_c(\lambda, l, b) = 0$ for $|b| > 20^\circ$ and $\lambda = 25 \ \mu m$. 
The Incredible Weakness of Nozoding

- For a spherical shell at distance $R > 1$ AU from the Sun,

$$I \propto \left(1 - R^{-2} \sin^2 \theta\right)^{-0.5}$$

$$\Delta I_{rms}/\langle I \rangle \approx 0.04/R^2 < 1\% \text{ for } R > 2.$$  

- For a uniform density dust cloud with a cavity of radius $R > 1$ AU,

$$I_{bol} \propto \sin^{-1}(R^{-1} \sin \theta)/\sin \theta$$

$$\Delta I_{rms}/\langle I \rangle \approx 0.0125/R^2$$

Thus spherical components in the outer Solar System cannot be determined by applying the Weak No-Zodi Principle to DIRBE data.
Comparison of Zodi Models

Table 1: Intensities in the Lockman Hole
Intensity in MJy/sr in the Lockman Hole

<table>
<thead>
<tr>
<th>$\lambda$ [(\mu m)]</th>
<th>GOOD1</th>
<th>GOOD2</th>
<th>GOOD3</th>
<th>FIZZ1</th>
<th>FIZZ2</th>
<th>FIZZ3</th>
<th>FIZZ3P</th>
<th>REALITY</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.25</td>
<td>0.1364</td>
<td>0.1407</td>
<td>0.1501</td>
<td>0.1696</td>
<td>0.1694</td>
<td>0.1806</td>
<td>0.1797</td>
<td>0.2228</td>
</tr>
<tr>
<td>2.2</td>
<td>0.0942</td>
<td>0.0971</td>
<td>0.1037</td>
<td>0.1171</td>
<td>0.1170</td>
<td>0.1247</td>
<td>0.1240</td>
<td>0.1492</td>
</tr>
<tr>
<td>3.5</td>
<td>0.0770</td>
<td>0.0788</td>
<td>0.0856</td>
<td>0.0897</td>
<td>0.0913</td>
<td>0.0976</td>
<td>0.0974</td>
<td>0.1149</td>
</tr>
<tr>
<td>5</td>
<td>0.4287</td>
<td>0.4491</td>
<td>0.4699</td>
<td>0.4993</td>
<td>0.4954</td>
<td>0.5097</td>
<td>0.5088</td>
<td>0.5389</td>
</tr>
<tr>
<td>60</td>
<td>6.8324</td>
<td>7.2153</td>
<td>7.4800</td>
<td>8.3259</td>
<td>8.0314</td>
<td>8.6145</td>
<td>8.6166</td>
<td>8.7382</td>
</tr>
<tr>
<td>100</td>
<td>2.4155</td>
<td>2.5468</td>
<td>2.6346</td>
<td>3.0647</td>
<td>2.9380</td>
<td>3.1912</td>
<td>3.1932</td>
<td>4.1884</td>
</tr>
<tr>
<td>140</td>
<td>1.1585</td>
<td>1.2219</td>
<td>1.3091</td>
<td>1.4817</td>
<td>1.4246</td>
<td>1.5838</td>
<td>1.5848</td>
<td>2.4480</td>
</tr>
<tr>
<td>240</td>
<td>0.3571</td>
<td>0.3769</td>
<td>0.4028</td>
<td>0.4622</td>
<td>0.4414</td>
<td>0.4923</td>
<td>0.4927</td>
<td>0.9459</td>
</tr>
</tbody>
</table>

Biggest uncertainty is from the zodi models: change of 8 out of 90 kJy/sr at 3.5 \(\mu m\) for different no-zodi principles.
DIRBE-2MASS Residuals at K: $\sigma = 1.83$ kJy/sr
DIRBE-2MASS Residuals at L: $\sigma = 1.43 \text{ kJy/sr}$
Dwek & Arendt (1998): $L_{-0.5K}$ (in Jy) is very smooth
Near IR Decomposition
Discrepancy between Counts & Measurements

- Rebecca Bernstein gets about $2 \times$ more optical extragalactic background light than one derives from the sum of the galaxy counts:

$$I_{counts} = \int S dN = \int S \left| \frac{\partial N}{\partial \ln S} \right| d\ln S$$

$$I_{obs} \approx 2 \times I_{counts}$$

- Wright gets about $(2 \pm 0.5) \times$ more near infrared cosmic background light than is expected from deep $K$-band counts.

Both measurement involve difficult and uncertain zodiacal light corrections but they use entirely different techniques.
2.2 $\mu$m Galaxy Counts

- K counts from Figure 1 of Madau & Pozzetti, MNRAS, 312, L9-L15 (2000)
- CADIS counts from Huang et al astro-ph/0101269
- Integral under fit gives 6.3 kJy/sr or 8.6 nW/m$^2$/sr
Aperture fluxes systematically low
I am the PI on WISE, an all-sky survey in 4 bands from 3.4 to 22 µm. WISE found the closest stars to the Sun, the most luminous galaxies in the Universe, and also measured 100’s of millions of galaxies that contribute to the CIRB.

WISE launched 14 Dec 2009, and released an all-sky survey on 14 Mar 2012.
M31-sized halo from Via Lactea
There is no blank sky between galaxies
Cosmic Optical & IR Background
\( \gamma \)-Ray Connection

- The reaction \( \gamma_1 + \gamma_2 \rightarrow e^+ + e^- \) has a threshold of \( E_1 E_2 > (m_e c^2)^2 \).
- The peak cross-section of \( 1.7 \times 10^{-25} \text{ cm}^2 \) occurs at twice the threshold energy.
- 1 MJy/sr corresponds to a photon density of 0.63 cm\(^{-3}\) oct\(^{-1}\).
- Expect absorption of \( \gamma \)-rays over distance of 3 Mpc for 1 MJy/sr, or \( 450/\lambda[\mu\text{m}] \) Mpc for 20 nW/m\(^2\)/sr, at \( E \approx 400\lambda[\mu\text{m}] \) GeV.
VERITAS

- Operating at Mt Hopkins base camp
- Four 12 meter diameter segmented mirror telescopes
- Competitive with HESS in Namibia
Ablaze in the distance

- Blazar H1426+428 has a flux of $4 \times 10^{-12}$ erg/cm$^2$/sec at $E > 1$ TeV.
- Redshift $z = 0.129$
- 96% $\gamma$-ray absorption at 1 TeV for my CIRB
- Many other blazars now known
- But see Kusenko Tuesday morning about the “proton tunnel”
Conclusions

• The CIRB has been detected in both the far IR and the near IR windows through the interplanetary dust, but measurements between 5-60 μm are impossible from 1 AU

• Bolometric OIR background is about 100 nW/m²/sr

• Ratio of optical plus near IR to the far IR is about 2:1

• Biggest uncertainty is the zodiacal light, & DESIRE, LZM or ZEBRA would help.
Discussion: $\Delta X$

- For UVO “Madau” curve, fuel burn over current energy density ratio is $f/U_o = 1.9$
- Current CIRB bolometric energy density is about 100 nW/m$^2$/sr
- Therefore $\Delta X = -0.033$
- Madau curve with Rowan-Robinson addon at high z burns more fuel at high redshift, so $f/U_o = 2.3$, $\Delta X = -0.04$
- At 1/3 solar from cluster gas, $\Delta X = -0.02$
- Do we need more baryons [CMB], more AGN, or less CIRB [zodi]?
White Dwarf Helium Reservoir?

- Oppenheimer et al. (2001) claim 3% of local halo in old WDs
  \[ \Delta X = -0.04h \frac{f_{WD}}{0.03} \frac{M_H}{5 \times 10^{11}} \frac{\ell_{ONIR}}{5.6h \times 10^8} \frac{3 \times 10^{10}}{L_{MW}} \]

- BUT Richer on 2 Apr 2001 withdrew the claimed detection of faint, high proper motion stars in the HDF [astro-ph/9908270]

- The Oppenheimer et al. objects do not have a halo velocity distribution, and can not be part of a spherical halo.
REFERENCES

COSMOLOGY TUTORIAL:
http://www.astro.ucla.edu/~wright/cosmolog.htm
http://www.astro.ucla.edu/~wright/CIBR

- DIRBE: http://www.astro.ucla.edu/~wright/DIRBE/
- SIRTF: http://sirtf.caltech.edu/
FIRAS measured the CMB spectrum

- Far InfraRed Absolute Spectrophotometer
- A differential polarizing Michelson interferometer
- Zero output when the two inputs are equal
- One input is either the sky or a very good blackbody, other is a pretty good blackbody
Hot diffuse plasma gives right spectrum but violates FIRAS limit on y. Source thought to be highly obscured AGNs.
Sunyaev-Zeldovich Effect

Hot electrons increase high $\nu'$s, decrease low $\nu'$s
FIRAS Final Spectrum

- SZ Effect $\propto y = N_e \sigma_T k T_e / m_e c^2 < 15 \times 10^{-6}$
- Bose-Einstein $\mu < 9 \times 10^{-5}$
- Energy from hot electrons into CMB < 60 parts per million
FIRAS Far IR Background

• Any proposed FIR background must be compatible with the limits on the CMB distortion.

• This means the FIRB is either small or similar to the galactic spectrum.

• The FIRAS fit to the $N_H = 0$ intercept of the high frequency channel, [astro-ph/9803021]

  $$I_\nu = 1.3 \times 10^{-5} (\nu/100)^{0.64} B_\nu (18.5 \text{ K}),$$

  fails with $\Delta \chi^2 = 22.6$ (4.75 $\sigma$)
No simple limit at 850 \( \mu \text{m} \)

- FIRAS fit fails with \( \Delta \chi^2 = 22.6 \) but \( I_{850} = 143 \text{ kJy/sr} \)
- Lagache et al. fit [astro-ph/9901059] is marginal with \( \Delta \chi^2 = 5.8 \) but \( I_{850} = 115 \text{ kJy/sr} \)
- The modified scaled Primack model on the next slide is fine with \( \Delta \chi^2 = 2.2 \) but \( I_{850} = 195 \text{ kJy/sr} \)
Cosmic Optical & IR Background

![Graph showing the mean intensity vs. frequency and wavelength. The graph includes data points and curves indicating peaks at 996, 34, and 59 THz.]
FIRAS measured the CMB spectrum

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