Spatial structure of the WMAP/Planck haze

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Outline

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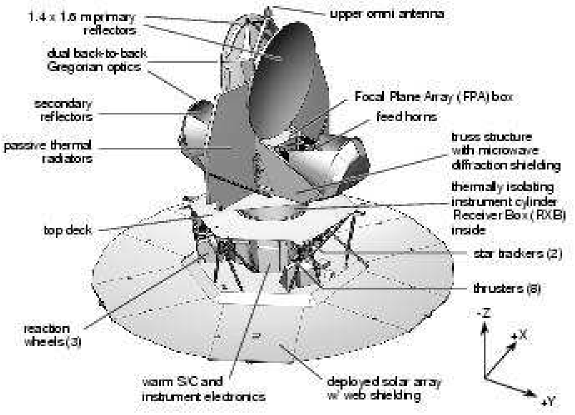
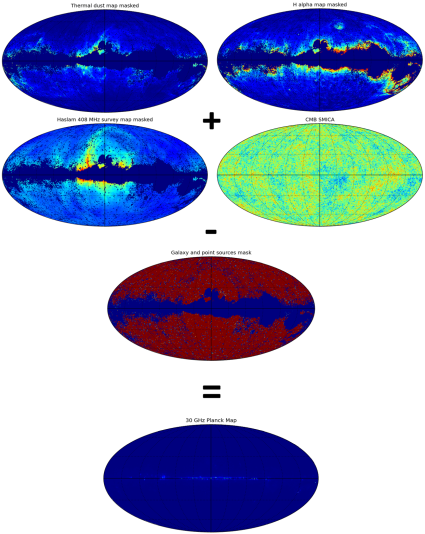
1. Introduction
   - Extended microwave emission at the Galactic center area according to WMAP data
   - Possible explanations for the WMAP/Planck haze
   - Gamma-ray emission – Fermi-bubbles
2. Data analysis
   - Template fitting
   - WMAP/Planck haze template
   - Mask
3. Data
   - ISM emission mechanisms
   - Planck microwave emission full-sky maps
4. Results
   - North-south asymmetry
   - Existence of substructures
   - Spectrum
   - Size of the WMAP/Planck haze

Extended microwave emission at the Galactic center area according to WMAP data

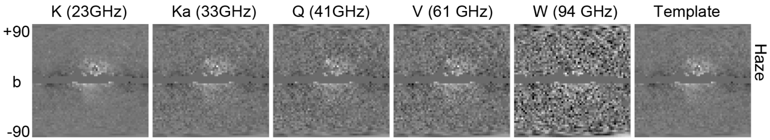
Wilkinson Miscrowave Anisotropy Probe (WMAP): launched in 2001, 9 years of operation. Full-sky maps: 23 GHz, 33 GHz, 41 GHz, 61 GHz, 94 GHz.



Extended microwave emission at the Galactic center area according to WMAP data



Extended microwave emission at the Galactic center area according to WMAP data

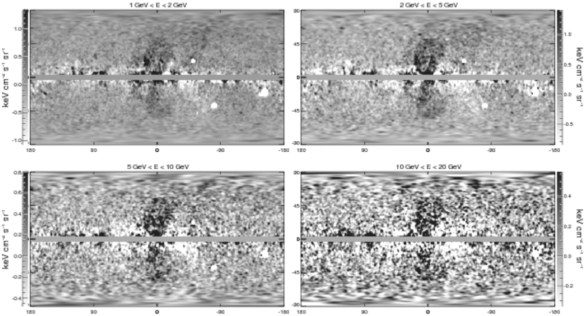


WMAP/Planck haze is a spherically-symmetric microwave emission extending to 20^o above and below the Galactic plane with hard spectrum ($E^2DN/DE \propto E^{0.1-0.2}$). It is observed at frequency range 20-50 GHz (D.P. Finkbeiner, "Microwave ISM Emission Observed by WMAP", ApJ 614 (2004) 186-193).

Possible explanations for the WMAP/Planck haze

- The existence of the WMAP/Planck haze may be caused by the excess of the radiation due to dark matter annihilation.
- Excess radiation may be produced by the Milky Way's population of pulsars. Pulsars are fast rotating neutron stars with their own magnetosphere which can be a source of electron-positron pairs.
- A common origin of observed radiation at the Galactic center region: WMAP/Planck haze, Fermi bubbles, soft X-ray emission, 2.3 GHz radio-emission. A characteristic property for such scenario would be a coincidence of spatial structures of WMAP/Planck haze and Fermi bubbles.

Gamma-ray emission – Fermi-bubbles



Fermi bubbles is a radially-symmetric emission in relation to the Galactic center extending to 50° above and below the Galactic center with a spectrum $dN/dE \sim E^{-2}$ (M. Su, T. R. Slatyer, D. P. Finkbeiner, “Giant Gamma-ray Bubbles from Fermi-LAT: AGN Activity or Bipolar Galactic Wind?”, Astrophys.J. 724 1044-1082 (2010)).

Outline

Template fitting

The initial map may be represented as:

$$d_i = a_j P_{ji} + x_i. \tag{1}$$

White noise makes a main contribution to noise maps of full-sky maps. It is statistically uncorrelated and it's covariation matrix is diagonal:

$$\langle d_i d_j \rangle = N_{\underline{i}} \delta_{\underline{i}j}, \tag{2}$$

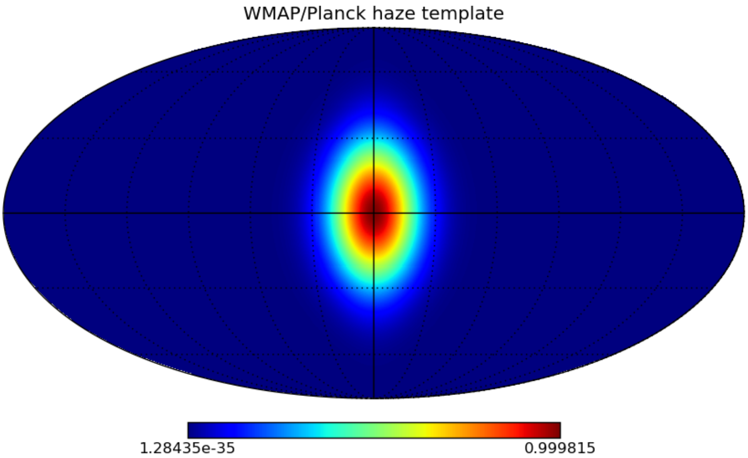
where N_i is a vector with length N_{pix}.
Chi-squared criterion:

$$\chi^2 = \sum_i \frac{x_i x_i}{N_i} = \sum_i \frac{\left(d_i - \sum_\alpha a_\alpha P_{\alpha i}\right)^2}{N_i}. \tag{3}$$

χ^2 minimum is obtained:

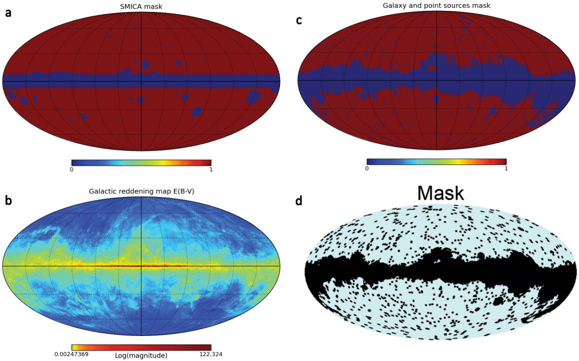
$$a_{\alpha'} = \left(P_{\alpha' i} N_i^{-1} P_{\alpha i}\right)^{-1} \left(P_{\alpha i} N_i^{-1} d_i\right). \tag{4}$$

WMAP/Planck haze template



2-D Gaussian ellipse with characteristic lengths $\sigma_l = 15^\circ$ и $\sigma_b = 20^\circ$.

Mask



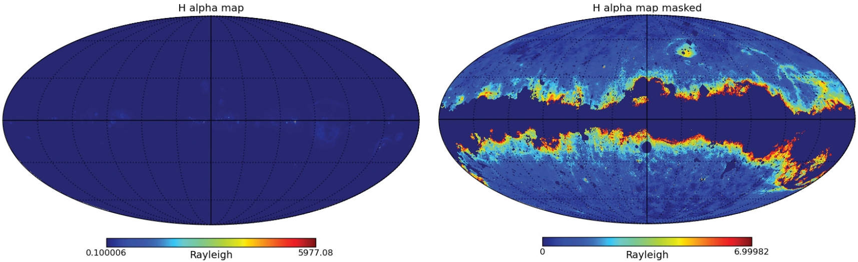
In addition, areas with galactic extinction greater than 1 mag and areas with H_α intensity greater than 10 rayleigh are covered.
The final mask covers 30, 8% of the sky.

Outline

ISM emission mechanisms

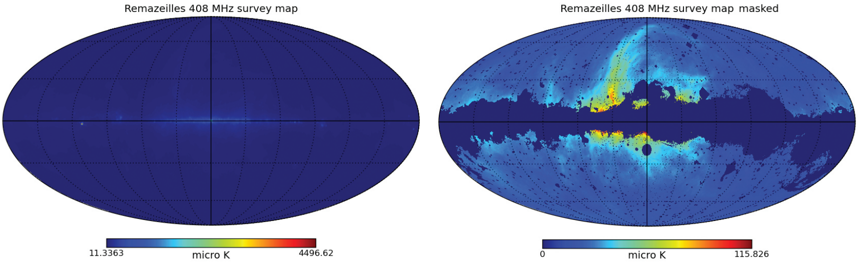
- Free-free emission
  At the regions of partially ionised hydrogen (H_{II}) electrons may interact with protons without recombination. They fly nearby, slow down and emit electrons. This process is called free-free or bremsstrahlung emission. H_{α} emission (Lyman line transition of ionized hydrogen) is used as a template for this mechanism.
- Synchrotron emission
  An emission of electromagnetic waves by charged particles which propagate in a magnetic field with relativistic speed. It is a consequence of basic law of electrodynamics, which states that every accelerated (decelerated) particle in magnetic field is a source of electromagnetic waves.
- Dust emission
  Interstellar dust consists of particles, including among their components silicon and carbon. An important dust property which allows to detect it is an ability to absorb and scatter light, it is called extinction.

Full-sky maps for ISM emission mechanisms: free-free



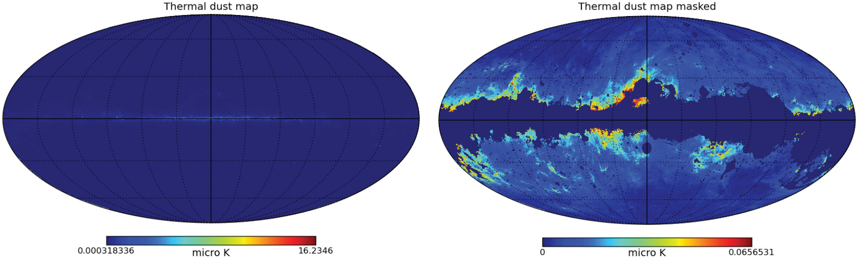
Finkbeiner H-alpha map (2003):Virginia Tech Spectral line Survey (VTSS), Southern H-Alpha Sky Survey (SHASSA) и Wisconsin H-Alpha Mapper (WHAM).

Full-sky maps for ISM emission mechanisms: synchrotron



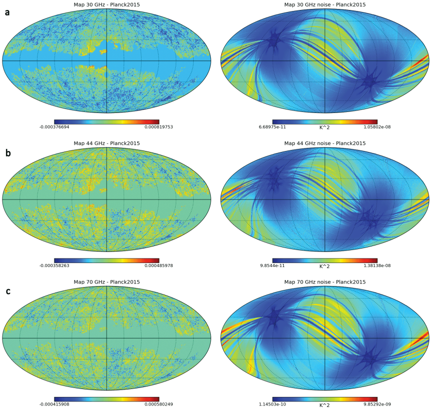
Haslam "408 MHz All Sky Continuum Survey": Effelsberg 100 metre telescope (northern hemisphere between declinations $-8°$ and $48°$), Parkes 64 metre telescope (southern hemisphere) and Jordell Bank MkIA telescope (polar part of northern hemisphere), recalculated in 2014 (Remazeilles et al., "An improved source-subtracted and destriped 408 MHz all-sky map").

Full-sky maps for ISM emission mechanisms: dust



Schegel, Finkbeiner, Davis: 100μm-map of submillimeter and microwave emission of diffuse interstellar Galactic dust, COBE/DIRBE и IRAS/ISSA.

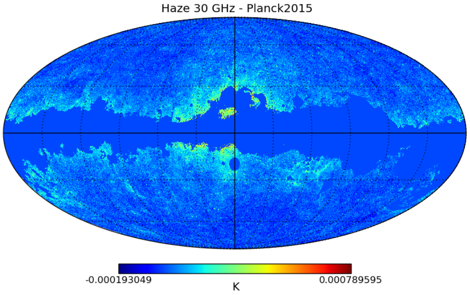
Planck microwave emission full-sky maps

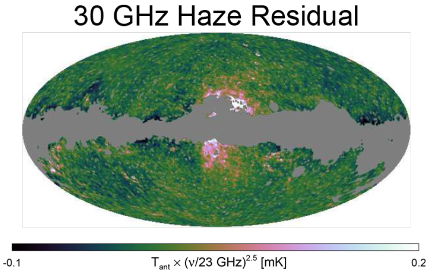


Ade et al. "Planck 2015 results. VI. LFI mapmaking", arXiv:1502.01585v1.

Outline

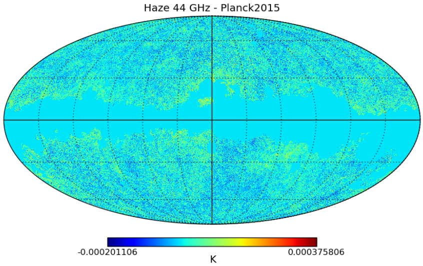
Derived emission: 30 GHz

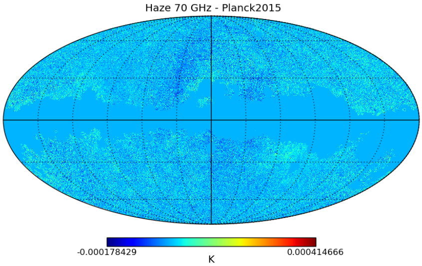




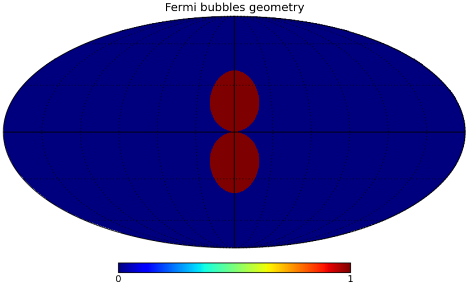
"Planck Intermediate Results. IX. Detection of the Galactic haze with Planck", (2012), astro-ph/1208.5483

Derived emission: 44 GHz and 70 GHz





North-south asymmetry

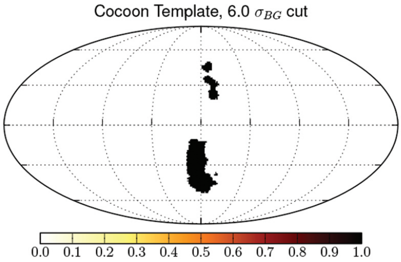


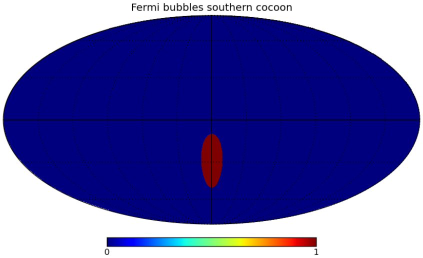
Intensity:

$$\begin{array}{lcl} \text{North} & - & (20.5 \pm 1.3) \times 10^{-5} \\ \text{South} & - & (10.4 \pm 0.5) \times 10^{-5} \end{array}$$

According to extracted data, WMAP/Planck haze emission is more intensive in northern hemisphere. But northern hemisphere is believed to be contaminated by unresolved sources.

Existence of substructures

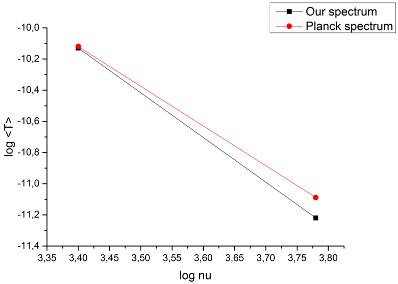




Mean intensity of southern cocoon – $(8.7 \pm 0.3) \times 10^{-5}$,
Mean intensity of southern bubble – $(7.99 \pm 0.2) \times 10^{-5}$,

The existence of substructures is not proved so far.

Spectrum

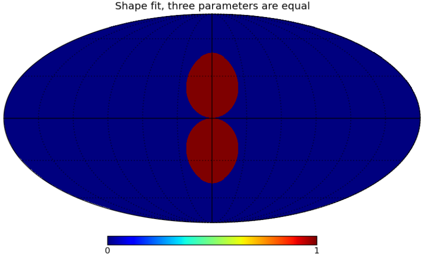


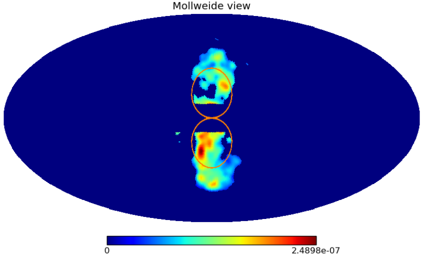
$$T_\nu \propto \nu^{\beta h}$$

$$\beta = -2.86$$

Planck (arXiv:1208.5483v1):$\beta = -2.55 \pm 0.5$

Size of the WMAP/Planck haze





$$\sigma_l = \sigma_b = b_0 = 17.9^\circ,$$

Sizes of the WMAP/Planck haze are in good agreement with the Fermi bubbles sizes.

Conclusion

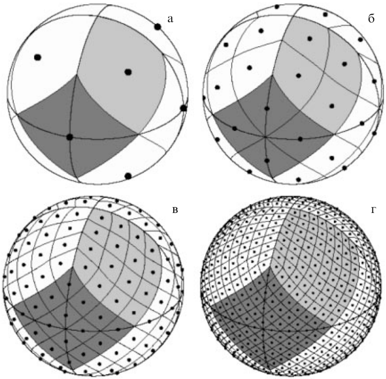
- The extended emission at the direction of the Galactic center is extracted at frequencies 30, 44 and 70 GHz. It's spatial structure for 30 GHz was studied in comparison to Fermi bubbles spatial structure.
- Up to now it is not possible to make a statement about the existence of substructures. The extension of the unmasked region is required.
- An estimate for size was obtained for the symmetric case: $\sigma_l = \sigma_b = b_0 = 17.9°$. It's consistent with the size of Fermi bubbles obtained by Fermi-LAT Collaboration (arXiv: 1407.7905v1).

Thank you for your attention!

Sky pixelization

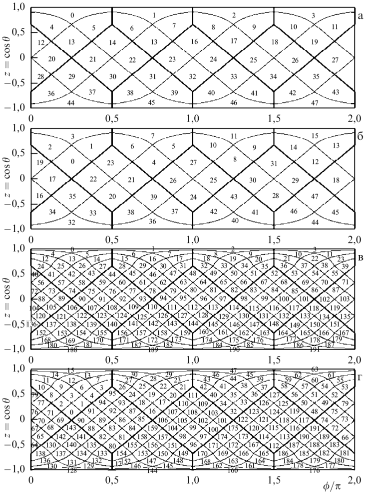
Sky pixelization is a presentation of a sphere as a merging of small area (pixels) according to a resolution.
Max Tegmark was the first to examine a question considering which pixelization scheme is preferable:
1) one should minimize the maximum distance d to the center of the nearest pixel. For example, in case of rectangular pixels, d is distance from corner points to the pixel centre;
2) the grid should provide a posibility of exact integration using values at lattice points.

HEALPix sky pixelisation scheme



HEALPix (Hierarchical Equal Area isoLatitude Pixelization) scheme is based on an oprimal choice of a shape of a pixel.
Three main criteria to a discrete lattice structure.
1) Hierarchial pixels structure.
2) Equal areas of discrete fragmentation elements.
3) Distribution of pixels of one row on a sphere along the same latitude.
Numbering of pixels on a map is made by using two indexation schemes: with ring or nested index.

HEALPix sky pixelisation scheme



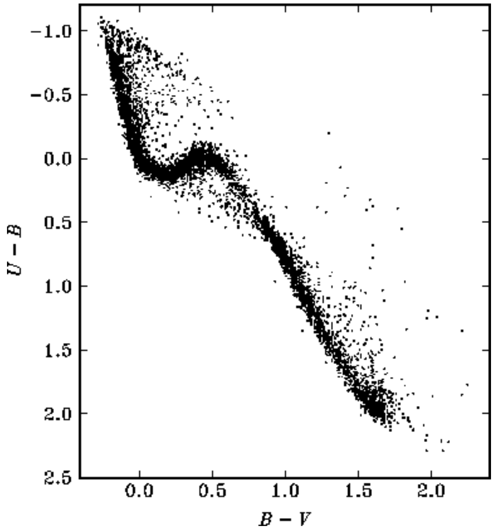
Two schemes of indexation on a sphere for HEALPix frid with resolution parameters $N_{side} = 2$ (a, b) и $N_{side} = 4$ (c,d). RING and NESTED schemes are shown.

Interstellar meduim extinction is an absorbtion, emission and scattering of elextromagnetic radiation by matter (dust and gas) in interstellar space between a radiating object and an observer. Visible reddening of radiation of distinct stars apperas due to this phenomena. Interstellar reddening can be describe in any photometric system as a colour excess. For example, in UBV system colour excess E_{B-V} for colour index $B-V$ can be shown as:

$$E_{B-V} = (B-V)_{observed} - (B-V)_{intrinsic}, \tag{5}$$

где $(B-V)_{observed}$ – observed colour index, $(B-V)_{intrinsic}$ – intrinsic colour index of a star.

Galactig reddening: two-colour diagram



H_α as a template for free-free

Valls-Gabaud has shown that brightness temperature T_{ff} of free-free emission in relation to H_α intensity line is:

$$\frac{T_{ff}}{I_{H_\alpha}} = \frac{1.56}{\nu_{30}^2} T_{30}^{0.317} 10^{0.029/T_4} \left(1 + \frac{n_{He_{II}}}{n_{He}} \frac{n_{He}}{n_H}\right) g_{ff}(\nu, T) \left(\frac{\mu K}{R}\right), \qquad (6)$$

where 1 $R = 10^6/4\pi$ photons in s$^-1$ cm^{-2} cp^{-1}, ν_{30} is frequency in relation to 30 GHz, T_4 is a temperature in relation to 10^4 K, $\frac{n_{He_{II}}}{n_{He}}$ is a fraction of ionized helium, $\frac{n_{He}}{n_H}$ – helium abundance, a g_{ff} – approximation og Gaunt correction factor:

$$g_{ff}(\nu, T) \approx 4.6 T_4^{0.21} \nu_{30}^{-0/14}. \qquad (7)$$

Approximation for the WMAP/Planck haze size

The WMAP haze sizes were approximated by two ellipses symmetric in relation to the Galactic plane with center at $l = 0,\ b = b_0$ и $l = 0,\ b = -b_0$.
σ_l, σ_b and b_0 are the parameters; squared function was minimized:

$$x\left(e_1, e_2\right) = map - e_1\left(\sigma_l, \sigma_b\right) * ellipse_1\left(\sigma_l, \sigma_b\right) - \\ - e_2\left(\sigma_l, \sigma_b\right) * ellipse_2\left(\sigma_l, \sigma_b\right), \quad (8)$$

where $ellipse1\left(\sigma_l, \sigma_b\right)$ and $ellipse2\left(\sigma_l, \sigma_b\right)$ are maps for up and down ellipses, e_1 and e_2 are projection coefficients of maps to ellipses
$e_i = \left(map, ellipse_i \times N^{-1}\right) / \left(ellipse_i, ellipse_i \times N^{-1}\right)$, N^{-1} – inverse noise covariation matrix.
Different constraints of minimization parameters lead to symmetry of the haze.