Observational Techniques

1: Detecting EM Radiation

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February 20, 2017

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Outline

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Why ASTR8011?

- The fundamentals of *observational* astronomy. The most common category of astronomer is an *observer* (others are theorists, instrumentalists and computational astrophysicists).
- Of course, the most successful astronomers can't be categorised so easily and cross these boundaries.
- We can not prod a star or do controlled experiments like in other areas of science. All we have to deal with are the waves and particles from space.

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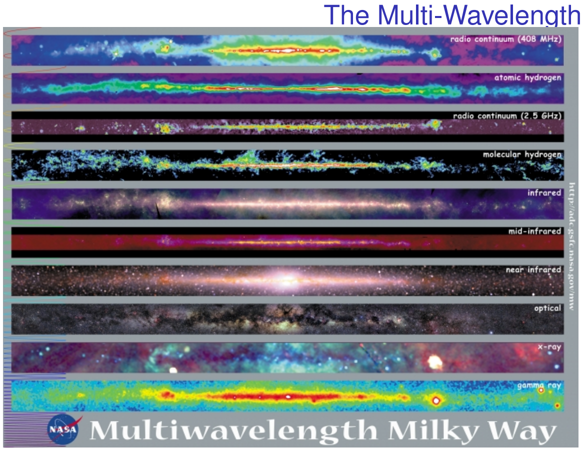
The Multi-Wavelength Sky



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Course Structure

There are 3 lecturers for this course. Fuyan Bian is primarily a high-redshift universe observational astronomer, Naomi McClure-Griffiths is primarily an observational radio astronomer. Nominal topics are:

- Detecting EM Radiation and Astronomical Units (MI)
- Signal-to-noise and Fundumental Backgrounds (MI)
- Telescopes and Co-ordinate Systems (MI)
- Astronomical Instruments and Detectors (MI)
- Imaging Data Reduction (FB)
- Imaging Photometry (FB)

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Course Structure (cont.)

- Practical Spectroscopy and SNR (FB)
- Spectroscopy Data Reduction (FB)
- Cross-correlation (FB)
- Observing Proposals (FB)
- Model Testing and Simulation (FB)
- Adaptive Optics and Optical Interferometry (MI)
- How Radio Telescopes Work (NM)
- Principles of Interferometry (NM)
- Radio Astronomy Calibration and Imaging (NM)
- Radio Astronomy Data Analysis (NM)

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Course Organisation

- Lecture notes will be made available at the Wattle site., and copied to: https://obstechanu.github.io/Observational-Techniques/
- There is no text, but one useful recommended reference is probably *Observational Astrophysics* by Robert Smith. Lecture notes will contain hyperlinks to other key references.
- Tutorial work will be mixed in with lectures, and from tomorrow *you are expected to have a laptop with you*.
- My email is michael.ireland@anu.edu.au, and my room W.025 (in most days).

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Assessment

- Observing Proposal Project (30%). Handed out by week 4.
- Two small homework assignments (MI, 15%)
- Three projects (2xFB, 1xNM, 55%)

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Who am I

You can find the papers I've published linked from my home page, or on NASA's *ADS abstract services*.

After finishing honours in 2002, I did a PhD largely on instrumentation for the Sydney University Stellar Interferometer (SUSI).

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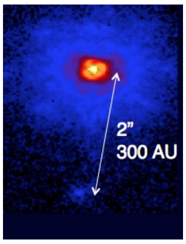
Who am I

I then went to the California Institute of Technology for a postdoctoral fellowship. Among other things I worked with the Keck telescope to directly detect planets and brown dwarfs around other stars.

I mostly split my time between instrumentation and observational astronomy.



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Who are you?

- Why are you doing this course?
- What do you think *Astronomy Research* is, and where do *Observational Techniques* fit in?

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Distance Units

- The mean distance between the earth and the sun is 1 AU (Astronomical Unit), or about 150 million km. It is *exactly* 149 597 870 700m. (IAU 2012 resolution)
- Stars are separated by distances of about 1 pc, which is the distance at which the *parallax* of a star is 1 arcsec (1/3600th of a degree). So 1 pc $\approx$ 206265 AU $\approx 3.086\times10^{16}$ m.

Notes

Solar or Object Units

- Stellar masses tend to be measured in units of $M_\odot^N$ (the *nominal* solar mass, IAU 2015 Resolution B3).
- Time is measured in seconds or years.
- e.g. Kepler's 3rd law for an arbitrary system is easy in solar units:

$$\frac{M_{\rm tot}}{M_\odot^N}\left(\frac{T}{1\,\rm yr}\right)^2 = \left(\frac{a}{1\,\rm AU}\right)^3. \quad (1)$$

- The nominal solar luminosity, $L_\odot^N = 3.828 \times 10^{26}$ W is roughly total radiative power (i.e. not counting Neutrinos) emitted from the sun.

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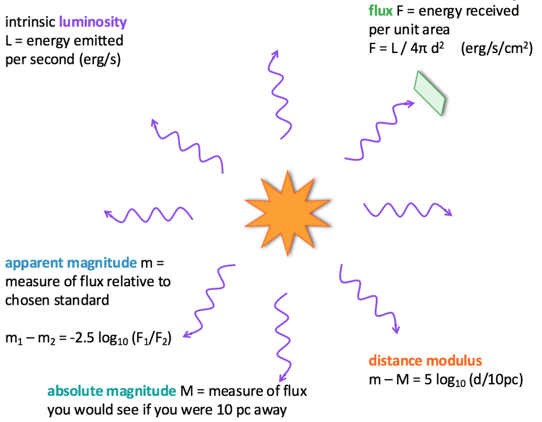
Luminosity and Flux



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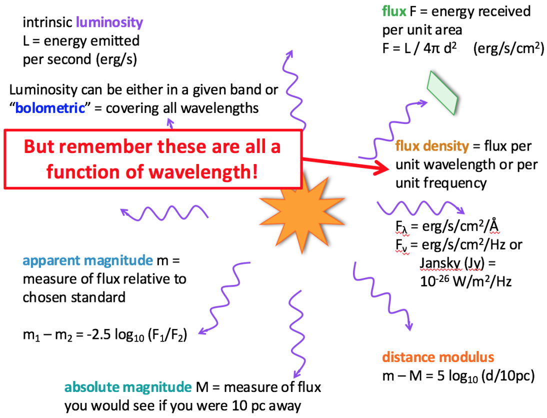
Luminosity and Flux



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Flux Units

- Units are either based on SI, or "cgs" (centimeters-grams-seconds). I will try to stick with SI units, but will not be consistent, and textbooks (and Fuyan) will not.
- 1 erg $= 10^{-7}$ Joule.
- Energy received through a telescope depends on wavelength (frequency) and telescope size.
- f_λ is the energy per unit time, per unit telescope area per unit wavelength.
- f_ν is the energy per unit time, per unit telescope area per unit frequency.
- The Jy = 10^{-26} W/m^2/Hz, a standard unit of f_ν in radio astronomy.
- Convert from frequency to wavelength based units: 1 W m^{-2} Hz^{-1} = 3×10^{14} / $\lambda^2(\mu$m) W m^{-2} μm^{-1}. Derive This
- Exercise A source has a flux density of 10 Jy at 11 μm. What is its flux density in W m^{-2} μm^{-1}, and in erg s^{-1} cm^{-2}Å^{-1} ? Later: What is its AB magnitude, and flux in photons s^{-1} m^{-2} μm? How about its Vega magnitude?

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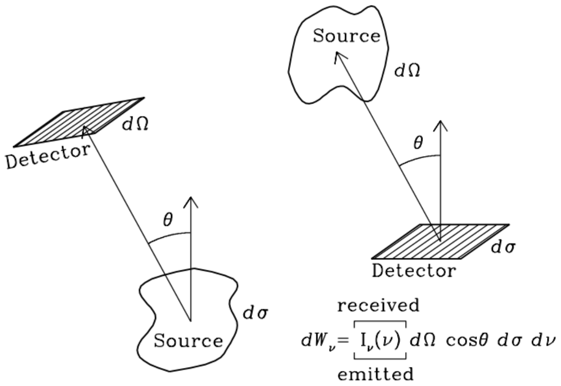
Specific Intensity or (Surface) Brightness

When looking at a resolved object, it is the *flux density per unit solid angle*, or specific intensity that is measured. (credit: NOAO)



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The Magnitude Scale

Many astronomers (e.g. me) use a historical scale called *Vega magnitudes*. These were once defined relative to the brightest star in the Northern hemisphere, α Lyrae or Vega. For any filter F, we have:

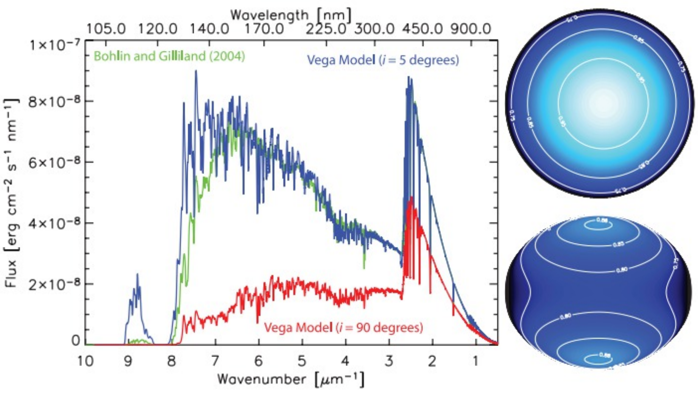
$$m_F = -2.5\log_{10}\frac{f_F}{f_{F,\mathrm{Vega}}} \quad (2)$$

$$f_F = f_{F,\mathrm{Vega}} 10^{-0.4 m_F}. \quad (3)$$

In practice, Vega doesn't have a Vega magnitude of exactly 0. It has a magnitude of 0.03 in the visible region of the spectrum. See Bessell and Murphy (2012) and Bessell (2005).

Notes

Why not Vega? (Aufdenberg 2006)



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Calibration from Allen

Astrophysical Quantities (Allen,4th edition) or Johnson (1965) gives some useful (approximate!) numbers for converting magnitudes to fluxes, e.g. for the V-band (visual, green) filter at ~550 nm wavelength, Vega has 10^{11} photons/μm/m^2/s.

	Johnson			
Band	λ (μm)	e_0 (W m^{-2} μm^{-1})	e_0 (Jy)	e_0 (Photons m^{-2} s^{-1} μm^{-1})
U	0.36	4.35×10^{-8}	1879	7.87×10^{10}
B	0.44	7.20×10^{-8}	4646	1.59×10^{11}
V	0.55	3.92×10^{-8}	3953	1.08×10^{11}
R	0.70	1.76×10^{-8}	2875	6.19×10^{10}
I	0.90	8.30×10^{-9}	2241	3.76×10^{10}
J	1.25	3.40×10^{-9}	1771	2.14×10^{10}
H	1.65	1.17×10^{-9}	1062	9.71×10^{9}
K	2.20	3.90×10^{-10}	629	4.31×10^{9}
L	3.40	8.10×10^{-11}	312	1.38×10^{9}
M	5.00	2.20×10^{-11}	182.5	5.53×10^{8}
N	10.2	1.23×10^{-12}	42.7	6.31×10^{7}
Q	21.0	—	—	—

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AB Magnitudes

Given how arbitrary the Vega-based magnitude scale is, there is a move in many modern missions (e.g. Hubble Space Telescope, HST) to move towards something more based on physics. An example is the AB magnitude system.

$$m_{\mathrm{AB}} = -2.5\log(f_\nu/3631\,Jy) \quad (4)$$
$$\approx -2.5\log(\mathrm{Jansky}) + 8.900. \quad (5)$$

... and so on (not actually sure which above definition, if either, is primary).
Q: What is the AB magnitude zero-point in cgs units?

Notes

Bolometric Magnitudes

- While we're on these units, the *bolometric* magnitude scale is still in use, because it enables total luminosity to be seen as a temperature correction to measured apparent magnitudes.
- Absolute magnitudes are defined apparent magnitude at a reference 10 pc distance.
- Reference quantities (IAU 2015 resolution 2) are:

$$L_0 = 3.0128 \times 10^{28}\,W \quad (6)$$
$$f_0 = 2.518\,021... \times 10^{-8}\,W\,m^2 \quad (7)$$

- Key equations are:

$$M_{\mathrm{Bol}} = -2.5\log(L/L_0) \quad (8)$$
$$m_{\mathrm{Bol}} = -2.5\log(f/f_0) \quad (9)$$

Notes

Temperatures

- *Temperature* can be tricky to define in astrophysics, as systems are not always in thermodynamic equilibrium.
- A *kinetic temperature* is often used : equate the mean "random" kinetic energy per particle to $\frac{3}{2}k_B T$.
- In the Universe as a whole, the coldest temperature without a fancy refrigerator is 3 K, defined by the temperature of the Cosmic Microwave Background (CMB). If you could arrange to be permanently in shadow of the sun (and planets etc) you can get to 3 K in our solar system. It is hard to get below about 10 K in the Galaxy.
- The kinetic temperature of the visible surface of the sun varies from 4100 K to $\sim$10,000K.

Notes

Blackbody Radiation

- One of the easiest ways to determine an objects temperature is to look at the radiation it emits. *Blackbody radiation* is the radiation emitted from a body that has perfect emissivity.
- One way to get near-perfect blackbody radiation is to punch a small hole in a cavity of uniform temperature. This evens out the effects of albedo variations.
- Astrophysics doesn't have perfect cavities... but we can talk about:
    1. The *effective temperature* of a surface is the temperature of an blackbody that would emit the same total radiation.
    2. The *brightness temperature* of a surface at wavelength λ is the temperature of a blackbody that would emit the same radiation at that wavelength.

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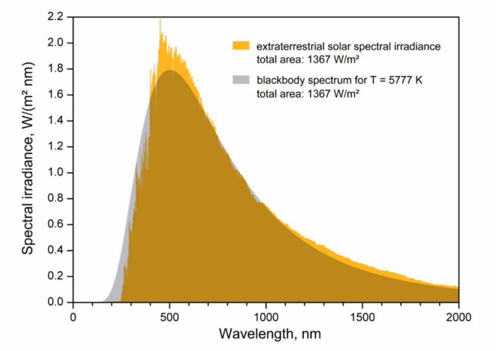
Solar Spectrum

The *sominal* solar values are $S^N_\odot$=1361 W m^{-1} and $T^N_{\mathrm{eff}\odot}$=5772 K.



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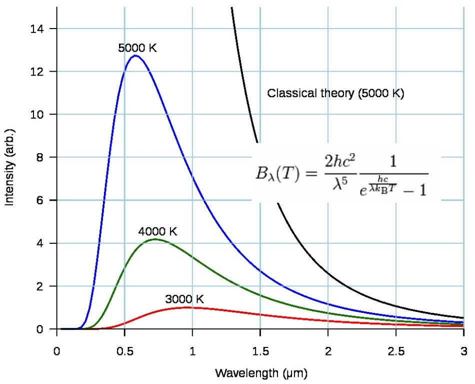
Planck's Formula



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The Two-Micron Photon

Little photon, warm and soft
You've come to us from far aloft.
An HI atom was your Mamma
(She used to call you *Brackett Gamma*).
But now a million years have passed –
How time flies when you go fast!

Your long wavelength made chances good
You'd make it through galactic mud.
Indeed you dodged the gas and dust;
Your motto was "The Earth or bust!"
No way would silicates deflect you,
The way they did your friends in blue.

Your little heart was filled with fear
As you plunged into our atmosphere.
"Holy cow!" you cried out loud:
"It's Siding Spring – but where's the cloud?!"
At last your journey's end was here –
The A.A.T. was looming near.

Boinng! Off the mirror! Up you go,
To secondary, then down below.
Yes – ATAC, with outstanding foresight,
Have I.R.P.S. on tonight.
(And certainly it was heroic
The way you bounced off the dichroic.)

You're really glad the window's made of sapphire.
(Glass really would have raised your ire.)
Indeed, it's hard to keep from gloating:
Such luxury – an A.R. coating.
Through apertures, and then – oh phew!
The C.V.F. was set for you.

Your journey over –suicide
In indium antimonide.
But onwards does your soul continue,
Electrically – you had it in you.
Ignoble fate for such a martyr
To end up in the Interdata.

We missed you, too – where were we?
We'd slipped outside to have a pee.

by John Storey

Notes

Photons and Quantum Mechanics

Whenever we want to add up the energy in an electromagnetic wave, we can only do so in discrete units - photons. Each photon has an energy equal to:

$$E = h\nu \tag{10}$$

$$= \frac{hc}{\lambda}. \tag{11}$$

Most astronomical measurements are about counting photons - the rate of photons arriving in a range of wavelengths (or frequency) tells us the about the energy output of the astronomical source at that wavelength (frequency) range.

Notes

Poisson Statistics

If the number of photons expected to arrive in a particular aperture from a particular range of angles in a particular wavelength (frequency) range is r, then the actual number of detected photons has a Poisson distribution:

$$P(N = k) = \frac{r^k e^{-r}}{k!} \tag{12}$$

Importantly, the variance of N is r, the standard deviation is $\sqrt{r}$, so:

$$S/N = \sqrt{r} \approx \sqrt{N} \tag{13}$$

Now work through a python example

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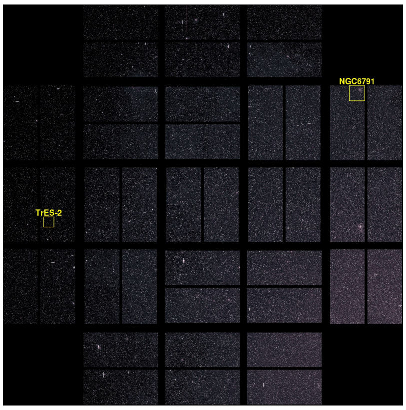
Poisson Statistics in the Kepler mission



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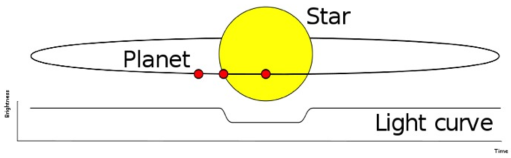
Poisson Statistics in the Kepler mission

Kepler stares at 150,000 stars, looking for tiny dips caused by a (dark) planet passing in front of the star. To be interesting, lets say that a 0.01% reduction in brightness due to an earth-like planet is needed to be measured at 5-σ.

How many photons do we need in the transit?



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Roughly how many photons would we receive from the sun between a 0.4 and 1 micron wavelength if it were placed at 100 parsecs , given that we receive $\sim$1 kW/m^2 from the sun at a distance of 1 AU?

Does this match the expectation from the Vega based calibration?

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What is a *background*?

- In observational astrophysics, a *background* refers to incoming light from an apparently empty region of the sky.
- In terms of geometry, the source of a background (e.g. scattered city lights) is often in the *foreground*. This is (one of many) unfortunate pieces of astronomical terminology.
- High backgrounds mean that it is more difficult to detect faint sources.

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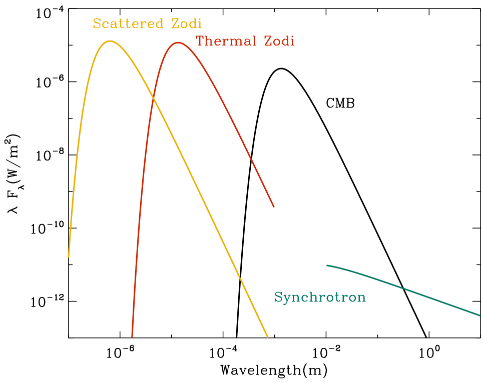
Key Backgrounds (from orbit)



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λf_λ and νf_ν plots

- On linear plots, we plot f_λ versus λ and f_ν versus ν. Why?
- Spectral energy distributions in astrophysics are often on log-log plots, but we still want to intuitively know how to integrate under a curve (at least roughly).
- For a region of the spectrum where $\nu F_\nu = K$ over a factor of e in frequency (or wavelength) starting at ν_0 and zero elsewhere, we have:

$$\int_{\nu_0}^{e\nu_0} F_\nu d\nu = \int_{\nu_0}^{e\nu_0} K/\nu d\nu \tag{14}$$

$$= K(\log_e(e\nu_0) - \log_e(\nu_0)) \tag{15}$$

$$= K. \tag{16}$$

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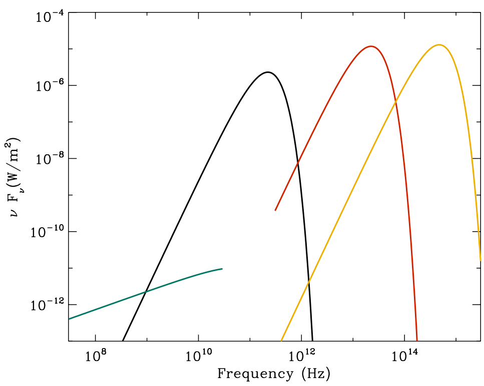
Key backgrounds as a νf_ν plot



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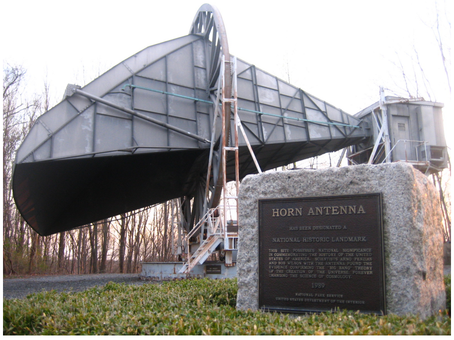
CMB

- The *Cosmic Microwave Background* (CMB) is left over radiative energy from the Big Bang and contains most of the radiation energy in the local universe. It has a temperature of 2.735K.
- It was discovered by Penzias and Wilson in 1958, at Bell Labs.



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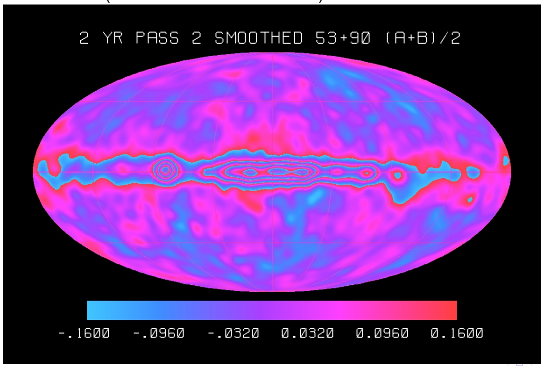
CMB (side comment)

The CMB is still actively studied today, and recent work was the subject of the 2006 Nobel Prize (the COBE NASA mission).



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Zodiacal Light

- The zodiacal light is emission concentrated in the *ecliptic* plane (the apparent plane where the sun and planets reside), and consists of scattered or re-emitted sunlight.
- The scattered light has the colour temperature of the sun (roughly), and the re-emitted light has the temperature of the earth (270K or so).
- Although the zodiacal light is only obvious around the zodiac, it contributes to background everywhere. Minimum background is 23.2 *magnitudes per square arcsec* (ref: HST/ACS manual for cycle 19).
  What does this unit mean?

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Zodiacal Light (APOD 0902)

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Galactic Synchrotron

- The Galactic synchtrotron emission is due to electrons spiralling in the magnetic field of our Galaxy. It becomes more significant than the CMB for frequencies below about 1 GHz.
- For all these backgrounds, there are regions of the sky were backgrounds are higher. My plots were designed to be roughly correct away from both the ecliptic and galactic planes.

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Other Backgrounds

- As you will learn later in the course (Fuyan), observing from the ground poses its own particular challenges. Not only are many wavelengths blocked by the atmosphere, but the atmosphere glows at many wavelengths, and scatters city lights and moonlight.
- There are also X-ray backgrounds, but they are much weaker... and have historically been dominated by unresolved extragalactic sources. In space-based ultraviolet and X-ray astronomy, if you detect a photon from *a particular sky location of interest* (what do I mean?), you can have a party because the backgrounds are so low.

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Summary

- In order to talk about astronomical observations and instrumentation, you need to know the meaning of *magnitude (Vega)*, f_λ, f_ν and be able to convert between units. You also need to understand *nominal* solar units and conversions.
- Estimating uncertainties are critical, and we will talk about *Signal-to-noise* in more detail from tomorrow.
- EM Radiation can be detected by counting photons. These events are described by *Poisson statistics*.
- Detecting faint objects is made difficult by astrophysical backgrounds. Key backgrounds are Galactic synchrotron, the Cosmic Microwave Background, and thermal/scattered Zodiacal light.

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