Radio Astronomy

- 電波天文學（Radio Astronomy）
- 授課：
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  - 週四 2:10PM-5:00PM
  - NCUIoA S4-914/ASIAA Rm716

Radio Astronomy

1	02/21	Radio Astronomy Fundamentals
2	02/28	Holiday
3	03/06	EM wave properties
4	03/13	Radio telescope fundamentals
5	03/20	Radio telescopes - single dish and interferometers
6	03/27	Radio telescopes - single dish and interferometers
7	04/03	Holiday
8	04/10	Radiative Processes - continuum and line/ thermal and non-thermal
9	04/17	Galactic Radio Astronomy - The Radio Sky and SNR [Synchrotron radiation]

Radio Astronomy (cont'd)

10	04/24	Mid-Term Exam
11	05/01	Galactic Radio Astronomy - HII regions [Bremsstrahlung radiation, Recombination lines]
12	05/08	Galactic Radio Astronomy - Molecular Clouds, Star Formation, and Chemistry [Molecular Transitions]
13	05/15	Galactic Radio Astronomy - Molecular Clouds, cont.
14	05/22	Galactic Radio Astronomy - Masers, Magnetic Fields [Polarization]
15	05/29	Galactic to Extragalactic Radio Astronomy - Radio Galaxies, HI Clouds [21cm line] and Molecular Clouds
16	06/05	Extragalactic Radio Astronomy - CMB and SZ Effect [Inverse Compton Scattering]
17	06/12	Radio Stars, Pulsars, SETI, Modern Radio Telescopes, etc
18	06/19	Final Exam

References:

- Main References :
  - Tools of Radio Astronomy
    - Rohlfs and Wilson, 2004 4th Edition
  - Radiative Process in Astrophysics
    - Bybicki and Lightman, 1979
- Additional Material :
  - Radio Astronomy
    - Kraus, 1986, 2nd Edition
  - Galactic and Extragalactic Radio Astronomy
    - Verschuur and Kellermann, 1988, 2nd Edition
  - Observational Astrophysics
    - Pierre Lena, 1988

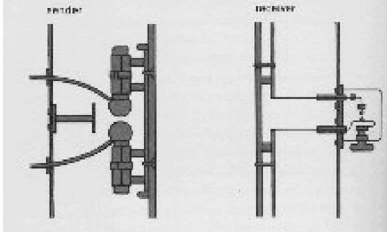
Rules?

- Grades :
  - homework/attendance : 20%
  - project : 20%
  - mid-term exam : 30%
  - final exam : 30%

Radio Astronomy Fundamentals

- Early History
- The Atmospheric Window

The Early History

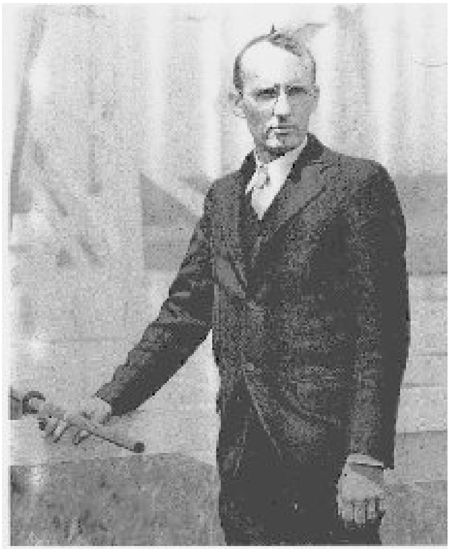


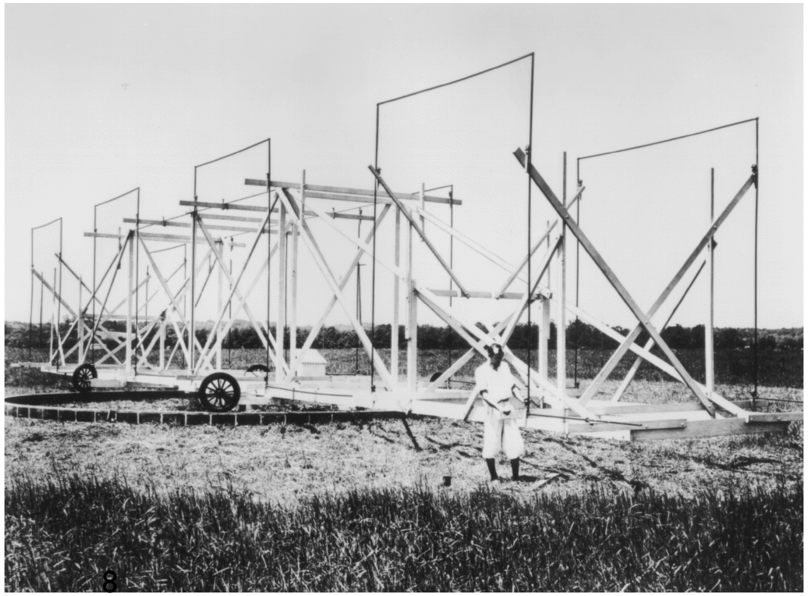
Once it was shown that the quantity that oscillates in a light wave is the electric field or the magnetic field, Heinrich Hertz artificially produced waves of different wave length from those of visible light. Above are his oscillator, or sender, and his resonator, or receiver.

- James Clerk Maxwell (1831-1879)
    - Maxwell's Equations [1860s-1870s]
- Heinrich Hertz (1857-1894)
    - transmitter of 5 meters in length [1888]
- Thomas A. Edison (1847-1931)
    - First proposal on record to detect Solar radiation in radio [1890]
- Sir Oliver J. Lodge (1851-1940)
    - (perhaps) First attempt to detect cm waves from the Sun [1897-1900]
- J. Wilsing (1856-1943) and J. Scheiner (1858-1913)
    - First journal paper on an attempt to detect radio wave from the Sun [1896]
- Charles Nordman [1900]
    - An improved attempt to the above (as Nordman thought) experiment
- Max Planck (1858-1947)
    - Plank's Law, quantization of radiation energy
- Oliver Heaviside (1850-1925) together with Kennelly
    - Heaviside layer for long range radio communication [1925]
- Further radio experiments discouraged by the above two results
- Guglielmo Marconi (1847-1937)
    - First to send and receive signals across an ocean, from Newfoundland to Cornwall. Commercial radiotelephone later became available
    - 1909 Nobel prize (with Carl F. Braun)

The Early History

- Karl Jansky (1905-1950)
    - joined Bell Telephone Lab [1928] to investigate short wave (10m-20m) transatlantic radio telephone service, the source of static in particular.
    - The antenna for 20.5 MHz (14.5m) picked up three kinds of static:
        - nearby thunderstorms, distant thunderstorms, faint steady hiss of unknown origin
            - celestial but no the Sun giving the repeating period
            - cosmic signal from the Galaxy! [1933]
        - 30m dish proposed but not approved by Bell Lab, later came the great depression, no astronomer followed up the effort until...





The Early History

- Grote Reber (1911-2002)
  - ham radio operator
  - applied for jobs in Bell Lab to work with Jansky on cosmic radio waves in 1930s but was turned down.
  - Do it yourself! build a telescope (31.4 ft.) by himself in Wheaton, Illinois.
  - Parabolic dish reflector adopted for receiving a wide range of wavelengths/frequencies
  - failed at 3300MHz, 900MHz but succeeded at 160 MHz for confirming Jansky's discovery [1938]
  - sky survey [1938-1943] opened radio astronomy as a major research field after WWII.

The Early History

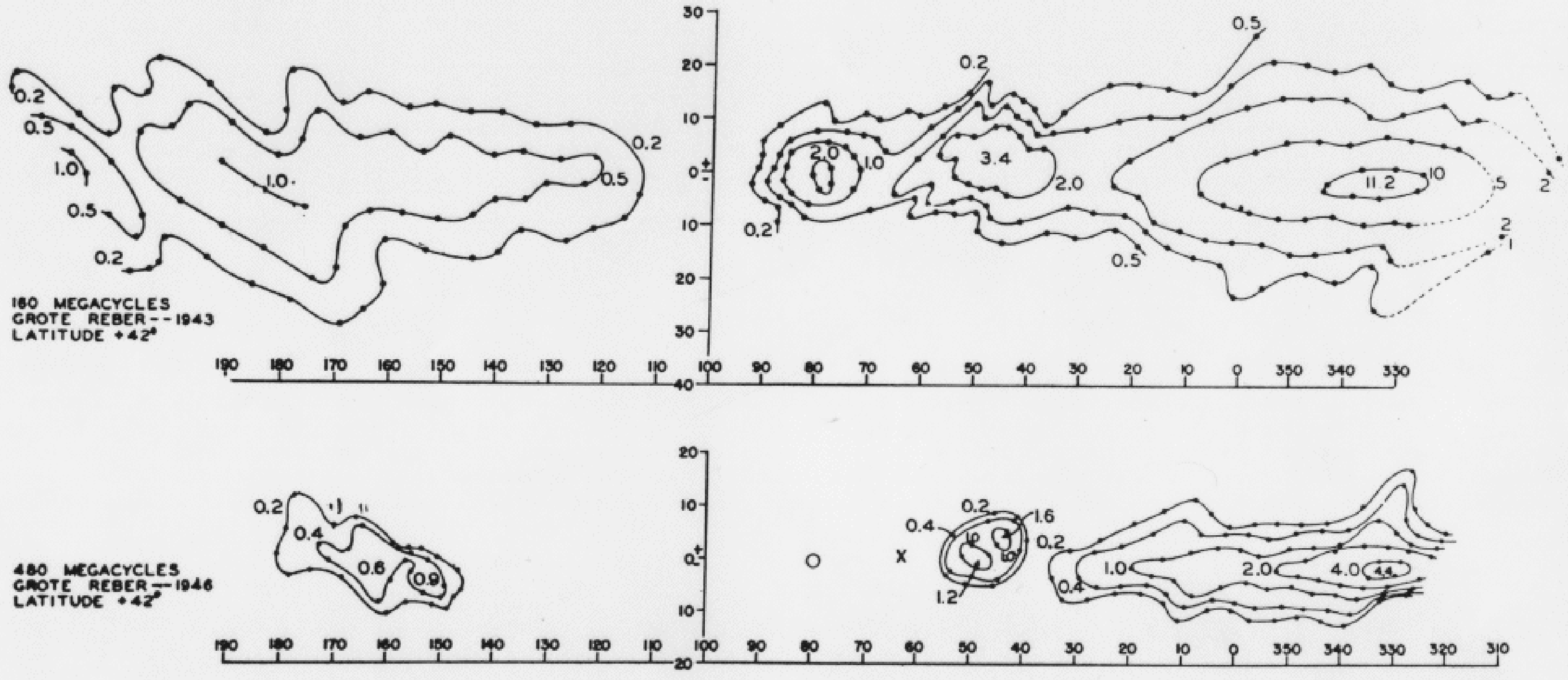


FIG. 7—Contours of constant intensity at 160 MHz and 480 MHz, taken at Wheaton, Illinois.

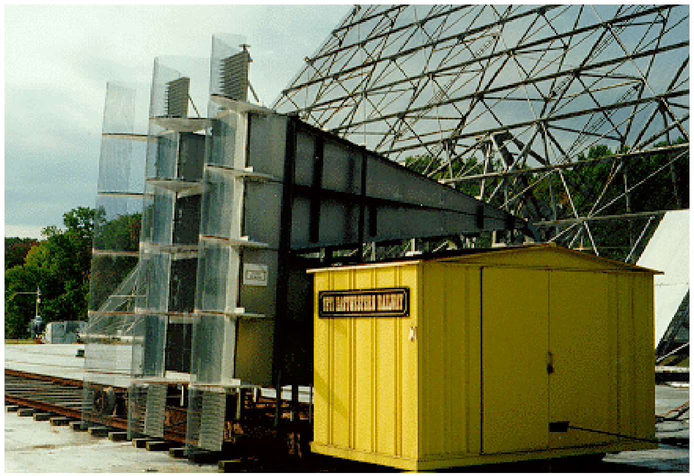
Galactic Radio Waves by Reber (Sky and Telescope 1949)

The Early History

- J.S. Hey
  - British Army Operational Research Group analyzing occurrences of radar jamming
  - Radio emission from the Sun as a source [1942]
- G.C. Southworth
  - thermal radio emission at centimeter wavelengths [1942]
- J.S. Hey, S.J. Parsons, J.W. Phillips
  - fluctuations of radio emission from Cygnus [1946]
- Oort (1900-1992) and van de Hulst
  - Prediction of 21 cm Line Radiation [1945]
- Harold Ewen (1922-) and Edward Purcell (1912-1997)
  - Discovery of the 21 cm Line [1950]
- John Bolton
  - Australia efforts in discovering discrete radio sources
- Sir Martin Ryle
  - Development of interferometric techniques

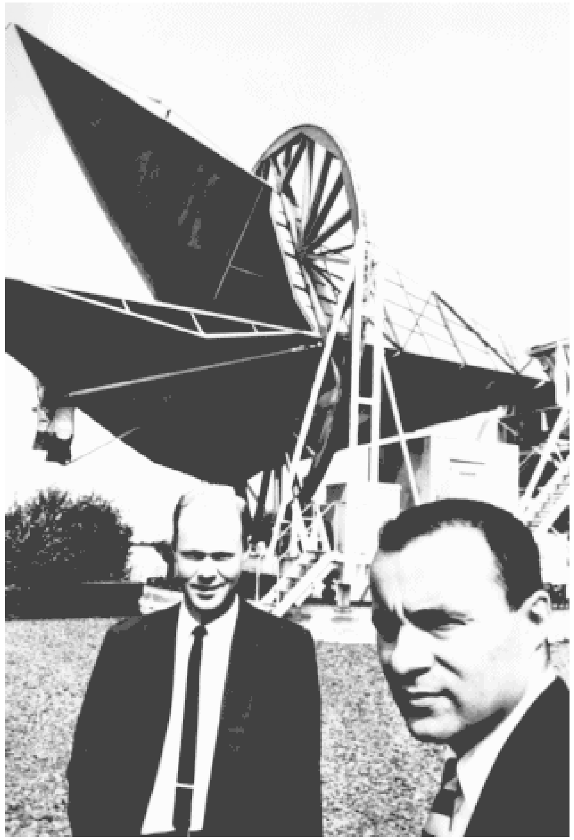
The Early History

- John Kraus (1910-2004)
  - radio engineer
  - led to the design and construction of the “Big Ear” telescope at Ohio Wesleyan Univ. (late 1950s), later began the Ohio State SETI program (1973)
  - The “Big Ear”
    - flat reflector ~ 110 m wide / 33m high
    - parabolic reflector ~ 120 m wide / 23 m high
    - ground plane ~ 120 m wide / 166 m long
    - equivalent aperture ~ 52.5 m
    - 1400 MHz, drift scan, beam-switching at 79 Hz



The Early History

- Arno Penzias (1933-) and Robert Wilson (1936-)
  - discovery of Cosmic Microwave Background with the 6m antenna [1965]
  - 1978 Nobel prize
- Jocelyn Bell-Burnell (1943-) and Antony Hewish (1924-)
  - discovery of radio pulsars predicted by theories of stellar evolution [1967]
  - 1974 Nobel prize (Sir Martin Ryle Antony Hewish with Sir Martin Ryle)



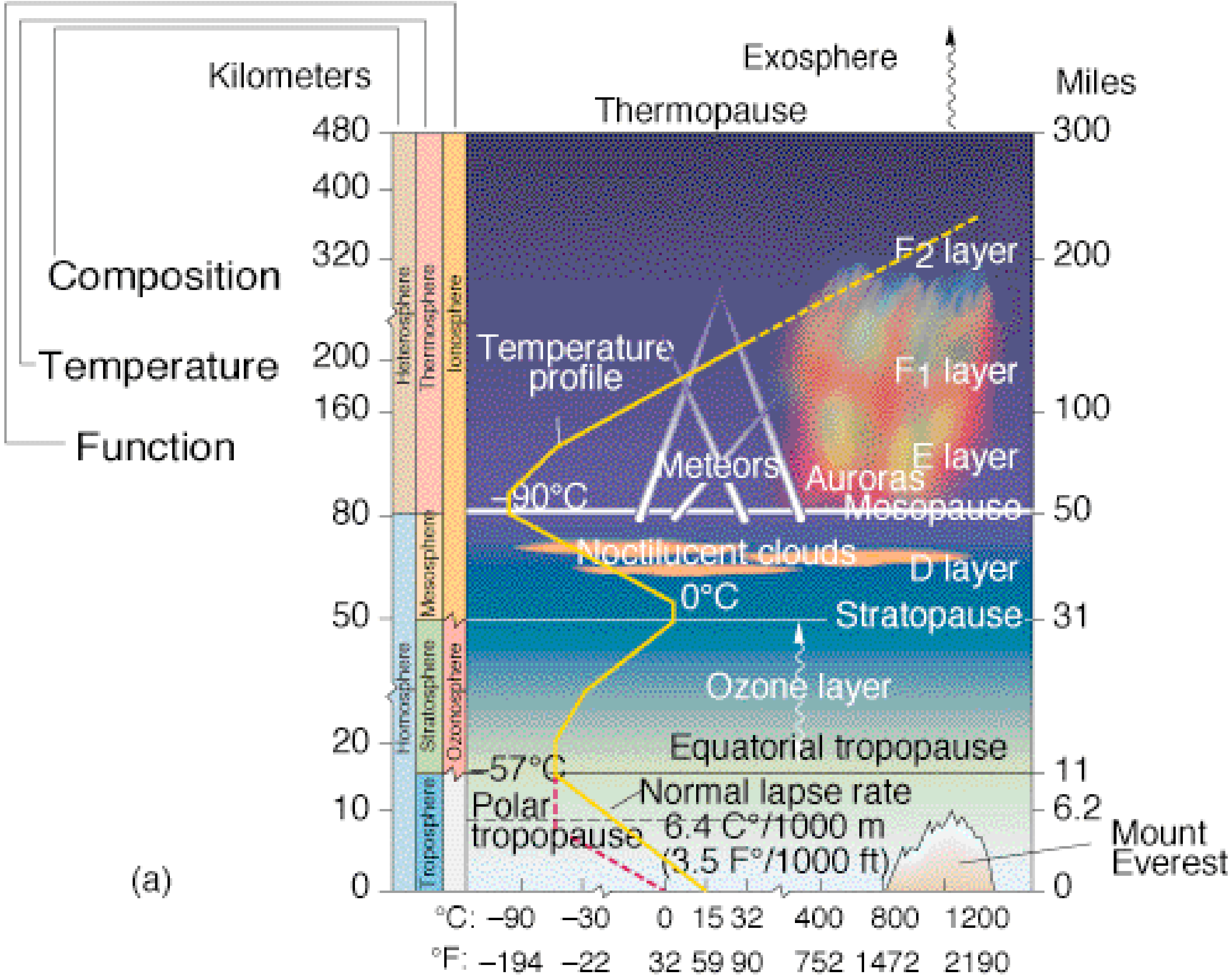
The Atmospheric Window

- Astronomy - The Observations and Studies of Celestial Objects
  - media
    - EM waves
    - particles (cosmic rays, neutrinos, ions, dust...)
    - Gravitational waves?
  - procedure
    - detection
    - calibration/analysis
    - imaging (if possible)
    - interpretation

The Atmospheric Window

- Ground-based
  - easy access, low cost
  - Traditionally, only optical window being utilized
  - Limited by the atmosphere
    - absorption (opacity)
    - (thermal) emission
    - scattering
    - turbulence
    - ionization
  - Limited by human interference
  - knowledge of both factors above is critical for observatory site selection
- Space-based
  - ideal location but difficult to access and extremely expensive

The Atmospheric Window



(a)

The Atmospheric Window

- Atmospheric structure (below 90 km)

$$P(z) = P_0 \; exp(-z/H_0)$$

$$H_0 = \frac{R}{M_0} \frac{T_m}{g}$$

$$R = 8.32 Joule \; K^{-1} \; mole^{-1}$$

$$M_0 = 0.029 \; kg$$

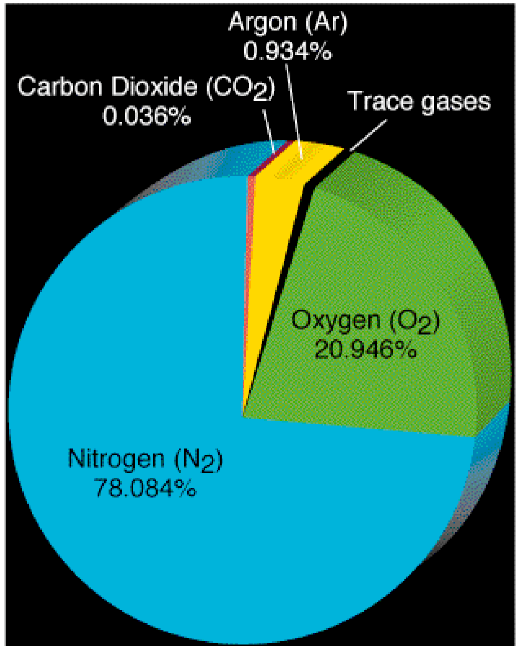
$$T_m = 273 \; K$$

$$g = 9.8 \; m \; s^{-2}$$

$$\Rightarrow H_0 \approx 7992 \; m$$

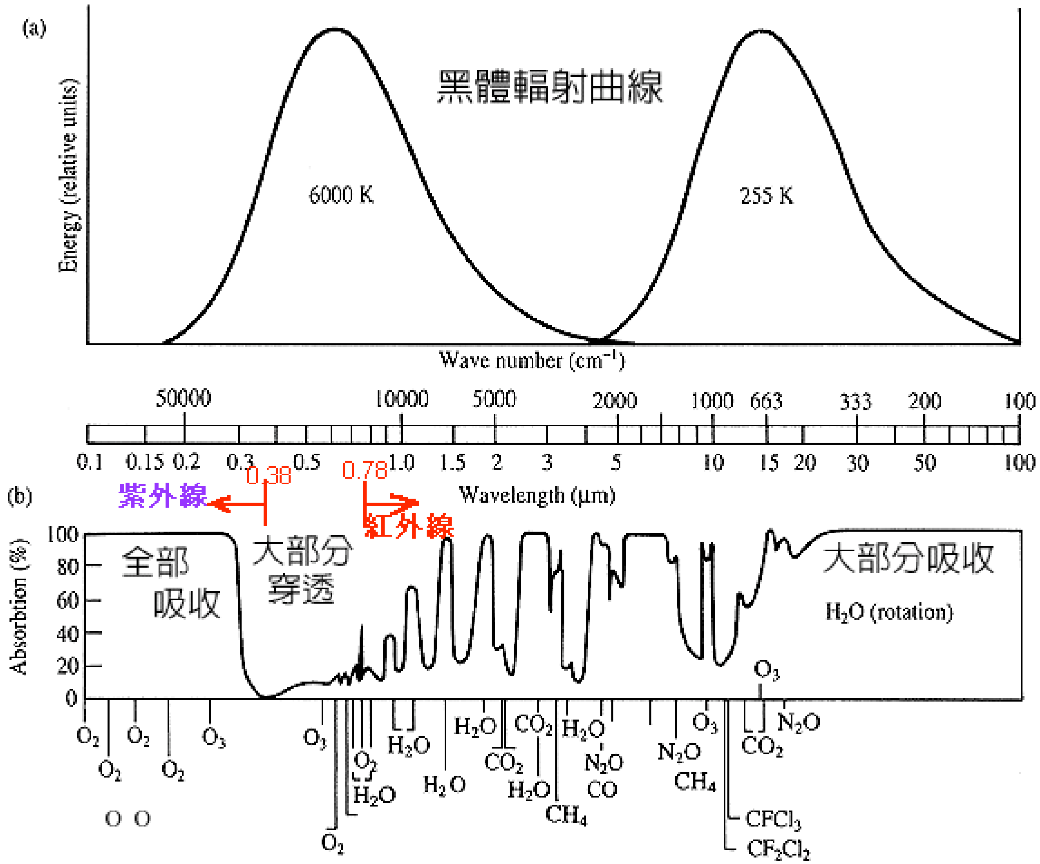
The Atmospheric Window

- Atmospheric constituents (below 90 km)
- Minor constituents
  - carbon dioxide - IR absorber
  - ozone - UV absorber, maximum concentration @ 16 km
  - water vapor - mixing ratio a strong dependence of temperature, thus altitude, scale hight ~ 3km
  - ions - significant ionization above 60 km via photochemical reactions, several ionospheric layers below 300 km, above that constant ionization up to 2000km
  - aerosols: solid (ice/salt crystals, soil particles) and liquid (water droplets)



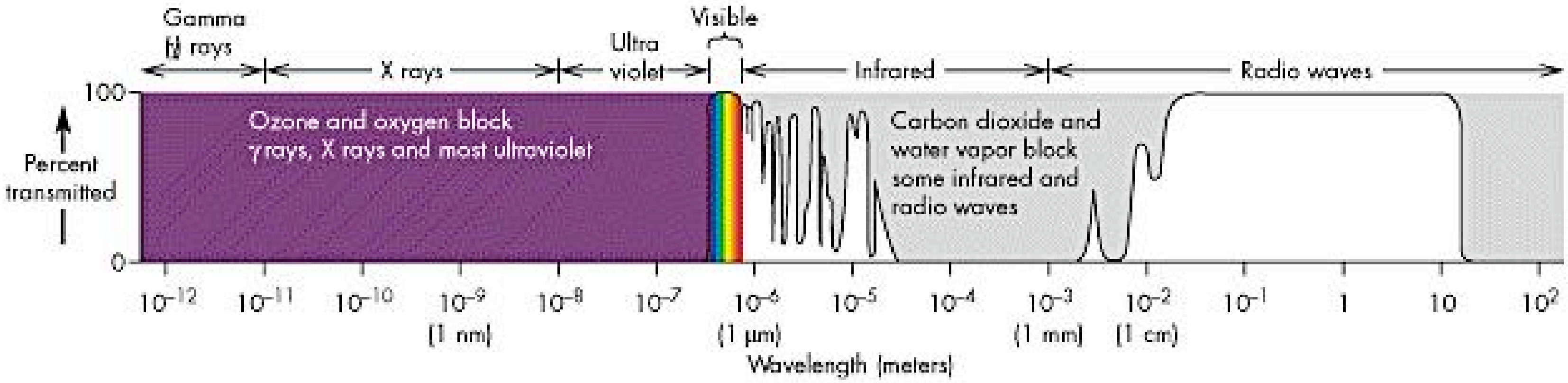
The Atmospheric Window

- Atmospheric absorption
  - absorber



The Atmospheric Window

- Atmospheric absorption
  - absorber
    - H_2O, CO_2, O_3, etc
      - (via pure rotational molecular transitions)
    - CO_2, NO, CO, etc
      - (via rotational-vibrational molecular transitions)
    - CH_4, CO, H_2O, O_2, O_3, etc
      - (via electronic molecular transitions)
    - O, N, etc
      - (via electronic transition of atoms/radicals)



The Atmospheric Window

- Atmospheric absorption
  - millimeter - pure rotational bands of H_2O, O_2
  - submillimeter/IR - rotational and rotational-vibrational bands of H_2O, CO_2
  - near UV - electronic transitions of O_2, O_3; continuum absorption of O_2
  - far UV - continuum absorption of N_2
- ground-based astronomy is limited to near UV (>300nm from a high site), visible, NIR (<25µm) with discrete bands, (sub) mm (>0.35mm) with non-negligible absorption, and centimeter and above

The Atmospheric Window

- Atmospheric absorption (in spectroscopic mode)
  - Telluric Bands
    - Lorentz profile due to pressure broadening
    - e.g. absorption by O_2, H_2O
  - Ionospheric Plasma
    - transparent to cm,mm wavelengths

The Atmospheric Window

- Atmospheric emission
  - thermal emission
    - below ~50 km where air density is high enough
    - optically thin blackbody radiation from the atmosphere
    - significant at NIR, (sub)mm
  - airglow by fluorescence light from recombination at upper atmosphere (100 km)
    - emitter OI, NaI, O_2, OH, H
    - continuous bland of emission lines
    - stratospheric OH radical in NIR with strong spatial variation
  - both sets limiting magnitude for observing faint sources
  - application of differential measurements
    - sky chopping, nodding, flat-fielding

The Atmospheric Window

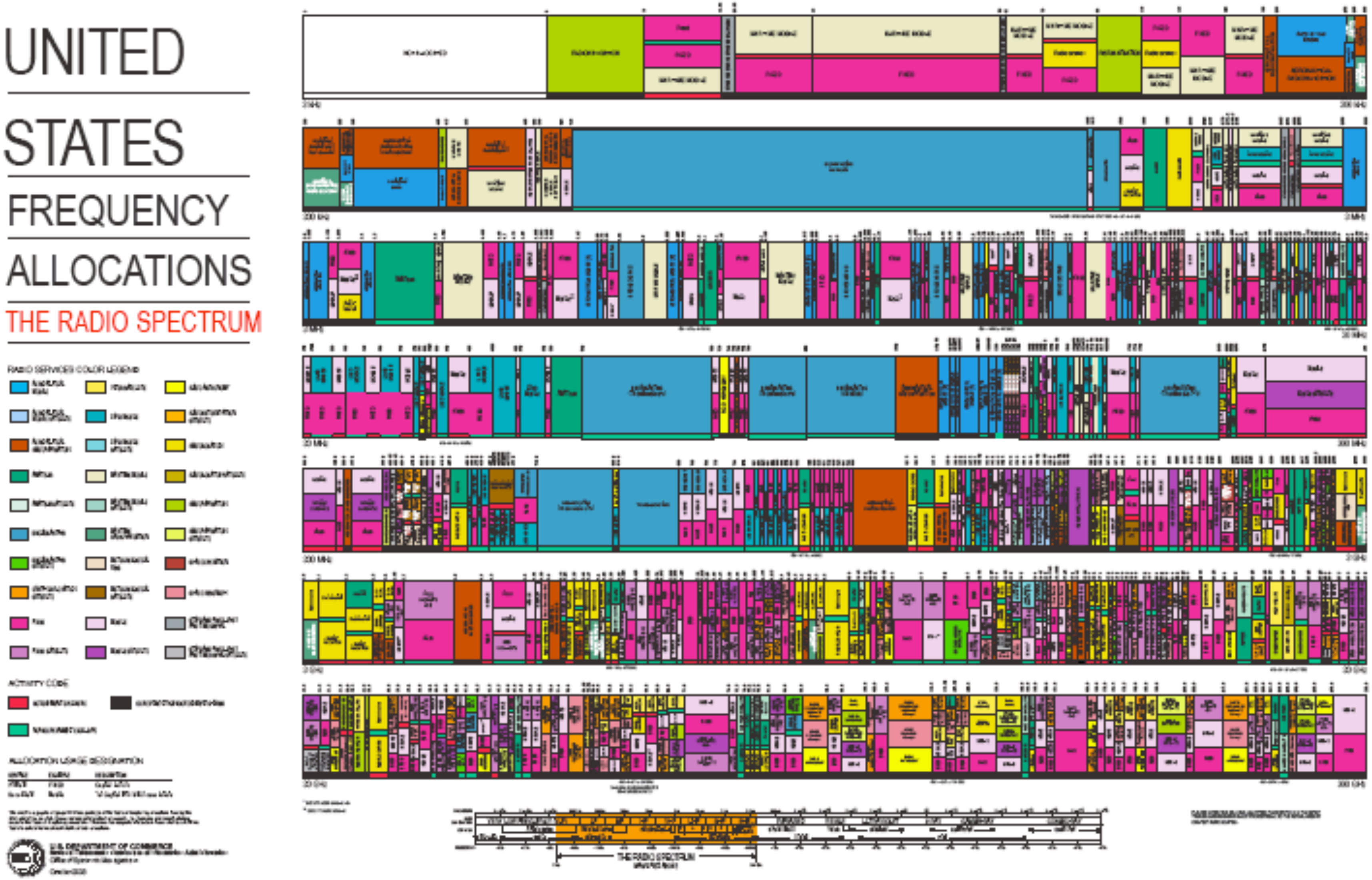
- Atmospheric scattering
  - resulted from molecules and aerosols
    - molecules: Rayleigh scattering in visible/NIR, anisotropic
    - aerosols: Mie's theory
- Comparing emission and scattering, there is a boundary above which emission always dominates - whether observing at day or night becomes insignificant
- Atmospheric turbulence
  - inhomogeneous both spatially and temporally
  - excited by ground surface, shearing...
  - temperature fluctuations and the air refractive index
- Atmospheric ionization
  - electron density fluctuations and the air refractive index
- Changes of refractive index due to the above fluctuations
  - seeing (position/size change), scintillation (intensity change)

The Atmospheric Window

- Human interference
  - light pollution
  - radio interference
    - ELF (3-30 Hz) : submarine communication
    - SLF (30-300 Hz) : submarine communication
    - ULF (300-3000 Hz) : mine communication
    - VLF (3-30 KHz) : submarine communication, avalanche beacons, wireless heart rate monitors
    - LF (30-300 KHz) : navigation, tim signal, LW
    - MF (300-3000 KHz) : AM
    - HF (3-30 MHz) : SW, amateur radio
    - VHF (30-300 MHz) : FM, TV
    - UHF (300-3000 MHz) : TV, mobile phone, wireless LAN
    - SHF (3-30 GHz) : microwave, wireless LAN, radars
    - EHF (30-300 GHz) : high-speed microwave radio relay
  - Space Pollution?!

Homework 1b: How does the long wavelength cutoff you find in 1a compare to the frequency allocation? Any application due to the cutoff?

The Atmospheric Window



Radio Astronomy Fundamentals

- BlackBody Radiation and Brightness Temperature

$$B_\nu(T) = \frac{2h\nu^3}{c^2}\frac{1}{e^{h\nu/kT}-1}$$

$$B_\lambda(T) = \frac{2hc^2}{\lambda^5}\frac{1}{e^{hc/k\lambda T}-1}$$

$$B(T) = \int B_\nu(T)d\nu = \int B_\lambda(T)d\lambda$$

$$= \frac{2h}{c^2}\int_0^\infty \frac{\nu^3}{e^{h\nu/kT}-1}d\nu$$

$$= \frac{2h}{c^2}(\frac{kT}{h})^4\int_0^\infty \frac{x^3}{e^x-1}d\nu$$

$$= \sigma T^4$$

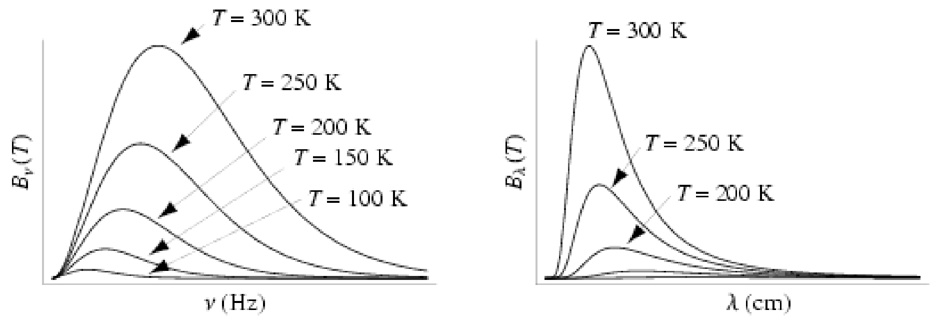
$$\sigma = \frac{2\pi^4 k^4}{15c^2h^3}$$

$$\nu_{max}(GHz) = 58.789(\frac{T}{K})$$

$$\lambda_{max}(cm)(\frac{T}{K}) = 0.28978$$

Radio Astronomy Fundamentals

- BlackBody Radiation and Brightness Temperature



Radio Astronomy Fundamentals

- BlackBody Radiation and Brightness Temperature

$$Wien\ Displacement\ Law$$

$$\frac{\partial B_\nu}{\partial \nu} = 0$$

$$\nu_{max}(GHz) = 58.789\left(\frac{T}{K}\right)$$

$$\frac{\partial B_\lambda}{\partial \lambda} = 0$$

$$\lambda_{max}(cm)\left(\frac{T}{K}\right) = 0.28978$$

$$Rayleigh - Jeans\ Law\ (h\nu << kT)$$

$$B_\nu^{RJ}(T) = \frac{2\nu^2}{c^2} kT$$

$$Wien's\ Law\ (h\nu >> kT)$$

$$B_\nu^{W}(T) = \frac{2h\nu^3}{c^2} e^{-h\nu/kT}$$

Radio Astronomy Fundamentals

- BlackBody Radiation and Brightness Temperature

$$B_\nu(T) = \frac{2h\nu^3}{c^2}\frac{1}{e^{h\nu/kT}-1}$$

Rayleigh – Jeans Law $(h\nu << kT)$

$$B_\nu^{RJ}(T) = \frac{2\nu^2}{c^2}kT$$

$$T = \frac{c^2}{2\nu^2 k}B_\nu^{RJ}(T)$$

check unit...

Brightness Temperature

$$T_b = \frac{c^2}{2\nu^2 k}B(T) = \frac{\lambda^2}{2k}B(T)$$

Think about 1. effective temperature, 2. color temperature...

Radio Astronomy Fundamentals

- BlackBody Radiation and Brightness Temperature

$$dE = I_\nu \cos\theta \; dt \; dA \; d\Omega \; d\nu$$

$$dW = I_\nu \cos\theta \; dA \; d\Omega \; d\nu$$

$dE = infinitesimal\ energy$

$dW = infinitesimal\ power$

$dt = infinitesimal\ time\ interval$

$dA = infinitesimal\ surface\ area$

$d\Omega = infinitesimal\ solid\ angle$

$d\nu = infinitesimal\ bandwidth$

$\theta = the\ angle\ between\ the\ normal\ to\ dA$
$and\ the\ direction\ to\ d\Omega$

$$I_\nu = specific\ intensity\ or\ brightness$$

check unit...

rate of energy transport, along a particular direction,
per unit area, per unit solid angle, and per unit frequency

Radio Astronomy Fundamentals

- BlackBody Radiation and Brightness Temperature

$$dW_1 = dW_2$$

$$dW_1 = I_{v1} d\sigma_1 d\Omega_1 dv$$
$$dW_2 = I_{v2} d\sigma_2 d\Omega_2 dv$$

$$S_v = \int_{\Omega_s} I_v(\theta, \phi) cos\theta d\Omega$$

$$1\ Jy = 1\ Jansky$$
$$= 10^{-26} W m^{-2} Hz^{-1}$$
$$= 10^{-23} ergs^{-1} cm^{-2} Hz^{-1}$$

$$d\Omega_1 = d\sigma_2 / R^2$$
$$d\Omega_2 = d\sigma_1 / R^2$$

$$dW_1 = I_{v1} d\sigma_1 d\sigma_2 / R^2 dv$$
$$dW_2 = I_{v2} d\sigma_2 d\sigma_1 / R^2 dv$$

$$I_{v1} = I_{v2}$$

Homework I

- 1.1 : Where is the cutoff at the long wavelength end for radio transmission in the atmosphere?
- 1.2 : What is the temperature equivalent of the energy, E, for 1 electron volt, that is, 1 eV. If this energy is contained in one photon, what is the wavelength of this phonoe? What is the frequency in units of Hz? A commonly used equivalent energy unit is cm^{-1}. What is the value for 1 eV in cm^{-1}?
- 1.3 : A unit commonly used in (radio) astronomy is flux density, S_ν. The usual unit for S_ν is Jansky (Jy), which is 10^{-26} W m^{-2} Hz^{-1}. Calculate the flux density in Jy, of a small angular size microwave source with an output of 600 W at a distance of 10 m, if the power is isotropically radiated and is uniformly emitted over a bandwidth of 10^6 Hz (= 1 MHz)?
- 1.4 : What is the flux density, S_ν, of a source which radiates a power of 600 W in the microwave frequency band uniformly form 2.7 GHz to 2.8 GHz, when placed at the distance of the Moon?
- 1.5 : Imagine that there is one kind of anti-collision radar installed on automobiles. It operates at around 70 GHz. The bandwidth is around 100 MHz, and at about a distance of 3 m, the power per area is 10^{-9} W m^{-2}. Assume the power level is uniform over the entire bandwidth, what is the flux density of this radar at 1 km distance? Typical radio telescopes can measure flux densities down to mJy level. At what distance will such radar disturb radio astronomy astronomy measurements?