Radio Astronomy -
Polarized Radiation

- Polarization (monochromatic wave case)
  - consider at an arbitrary position (r=0)

$$E = E_0 e^{-i\omega t}$$
$$= (\hat{x}E_1 + \hat{y}E_2)e^{-i\omega t}$$

$$E_1 = A_1 e^{i\phi_1} \ and \ E_2 = A_2 e^{i\phi_2}$$
$$E_x = A_1 cos(\omega t - \phi_1) \ and \ E_y = A_2 cos(\omega t - \phi_2)$$

  - draw figure

$$E_{x'} = A_0 \ cos\beta \ cos\omega t \ and \ E_{y'} = -A_0 \ sin\beta \ sin\omega t$$
$$-\pi/2 \leq \ \beta \ \leq \pi/2$$

$$(\frac{E_{x'}}{A_0 \ cos\beta})^2 + (\frac{E_{y'}}{A_0 \ sin\beta})^2 = 1$$

Radio Astronomy - Polarized Radiation

- Polarization and Stokes parameters (monochromatic wave case)

$$E_x = A_0(\cos\beta\ \cos\chi\ \cos\omega t + \sin\beta\ \sin\chi\ \sin\omega t)$$
$$E_y = A_0(\cos\beta\ \sin\chi\ \cos\omega t - \sin\beta\ \cos\chi\ \sin\omega t)$$

$$A_1\ \cos\phi_1 = A_0\ \cos\beta\ \cos\chi$$
$$A_1\ \sin\phi_1 = A_0\ \sin\beta\ \sin\chi$$
$$A_2\ \cos\phi_2 = A_0\ \cos\beta\ \sin\chi$$
$$A_2\ \sin\phi_2 = -A_0\ \sin\beta\ \cos\chi$$

$$I \equiv A_1^2 + A_2^2 = A_0^2$$
$$Q \equiv A_1^2 - A_2^2 = A_0^2\ \cos 2\beta\ \cos 2\chi$$
$$U \equiv 2A_1A_2\cos(\phi_1 - \phi_2) = A_0^2\ \cos 2\beta\ \sin 2\chi$$
$$V \equiv 2A_1A_2\sin(\phi_1 - \phi_2) = A_0^2\ \sin 2\beta$$

$$A_0 = \sqrt{I}$$
$$\sin 2\beta = \frac{V}{I}$$
$$\tan 2\chi = \frac{U}{Q}$$

$$I^2 = Q^2 + U^2 + V^2$$

Radio Astronomy - Polarized Radiation

- Polarization
  - polarization measurement
    - Linear feeds or Circular feeds

Linear Polarization

$$S_0 = I = E^2 = S$$
$$S_1 = Q = I cos\ 2\chi$$
$$S_2 = U = I sin\ 2\chi$$
$$S_3 = V = 0$$

Circular Polarization

right-handed (RCP)

$$S_0 = I = S$$
$$S_1 = Q = 0$$
$$S_2 = U = 0$$
$$S_3 = V = S$$

left-handed (LCP)

$$S_0 = I = S$$
$$S_1 = Q = 0$$
$$S_2 = U = 0$$
$$S_3 = V = -S$$

Radio Astronomy - Polarized Line Radiation

- Measuring magnetic fields - molecular line polarization
  - molecular line
    - Zeeman effect
      - Circular polarization
      - Zeeman, Lorentz (1902 Nobel prize)
        - line splitting
        - "strength" of B-field "along" the line of sight

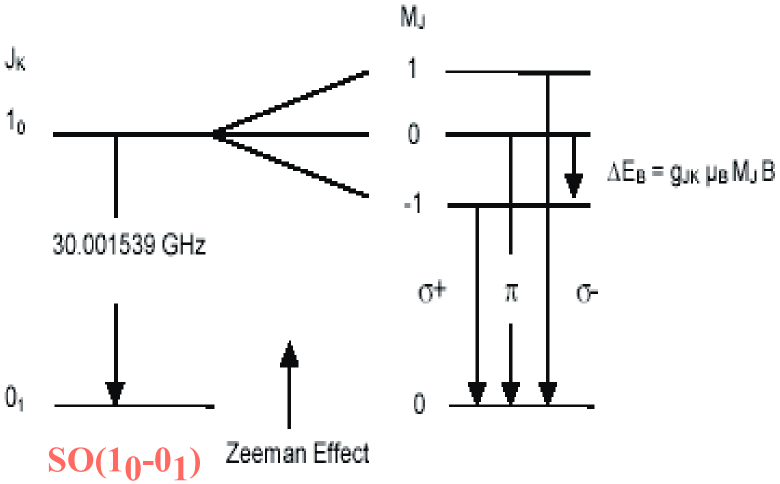
Radio Astronomy -
Polarized Line Radiation

Coutercy of Dr. C.C. Chiong

Zeeman effect

- Splitting of spectral lines into multiple components due to the coupling of an atom's or molecule's magnetic moment with an external magnetic field. σ+ and σ- has signals with different circular polarization. Different g factor for different molecules and transition.
- Suitable atoms or molecules are HI, OH, H_2O, CSS, CN, SO etc.

Most successful detection cases of Zeeman measurement are with HI, OH and H_2O.



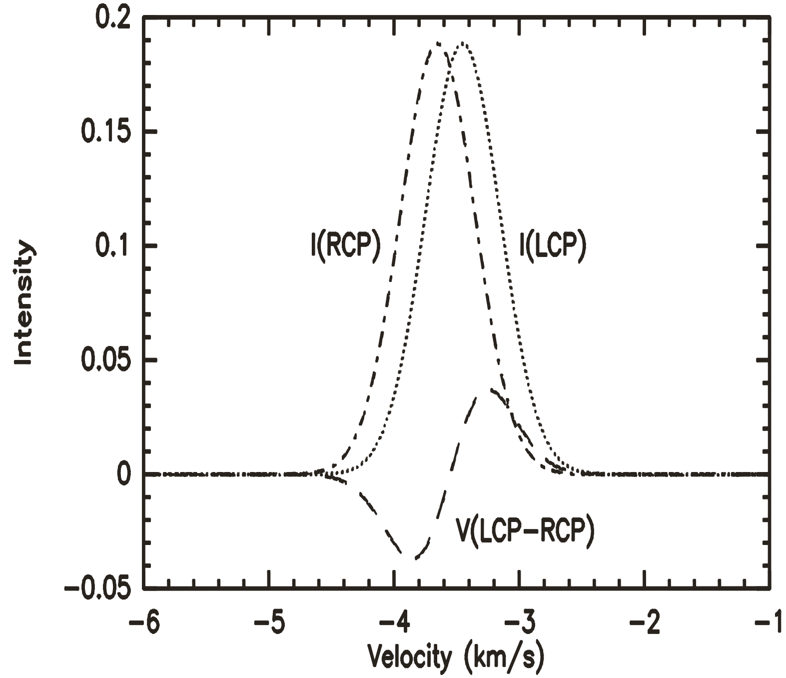
SO(1_0-0_1)

Radio Astronomy - Polarized Line Radiation

Coutercy of Dr. C.C. Chiong

Zeeman effect

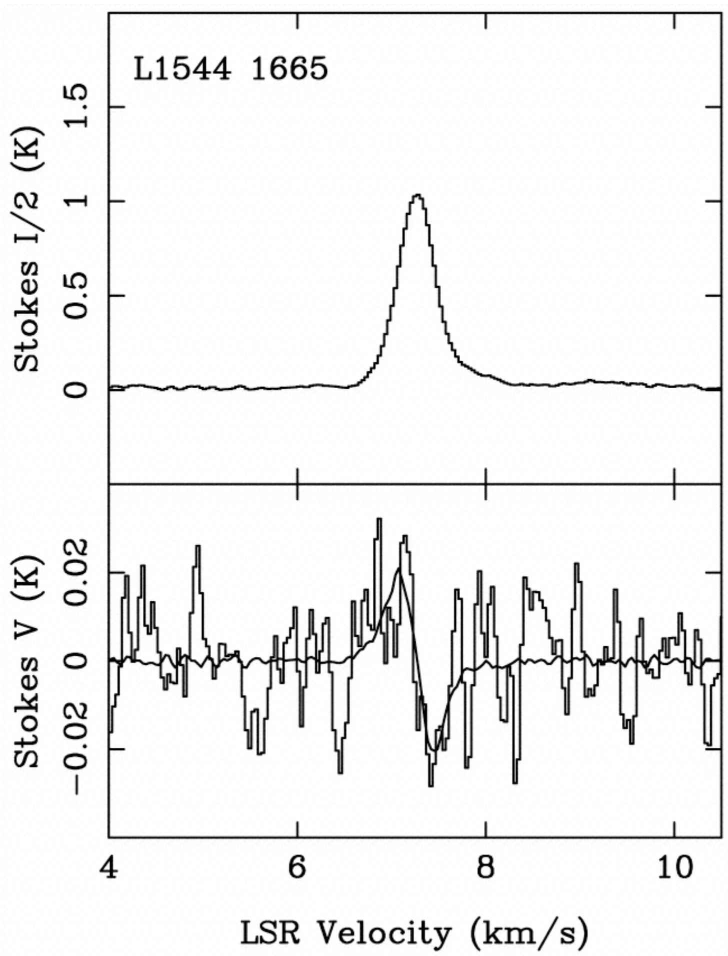
- If the splitting is large (RCP, LCP well separated), the total field strength can be derived (only OH and H_2O maser).
- If the splitting is small, it provides only the „line-of-sight" component B_{los}.



Radio Astronomy -
Polarized Line Radiation

Coutercy of Dr. C.C. Chiong

Zeeman effect



B(l.o.s.) ~ 10 micro Gauss

Crutcher and Troland 2000 ApJL

Radio Astronomy -
Polarized Line Radiation

Coutercy of Dr. C.C. Chiong

Current Status

• Bear in mind first that In most cases, only line-of-sight or plane-of-sky component is measured.

• Observational data supporting the existing star formation theories are still rare, because it is hard to measure the strength of interstellar magnetic fields.

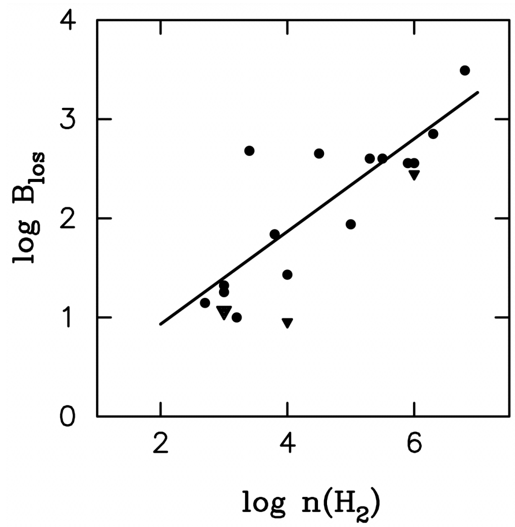
Theories :

The B-ρ relation: $|B| \propto \rho\kappa$,

κ = 1/2 to 1/3 (Mouschovias, 1985)

Observations :

Crutcher (1999) reviewed 15 detections and 3 upper limits towards the dense region.



$$B_{los} \propto \rho^{0.47\pm0.08}$$

Radio Astronomy -
Dust Emission

- dust
  - continuum emission - modified blackbody radiation due to the wavelength dependence of dust grain emissivity.

$$\tau_{dust} \propto \nu^{\beta} \ with \ \beta \sim 1 - 2$$

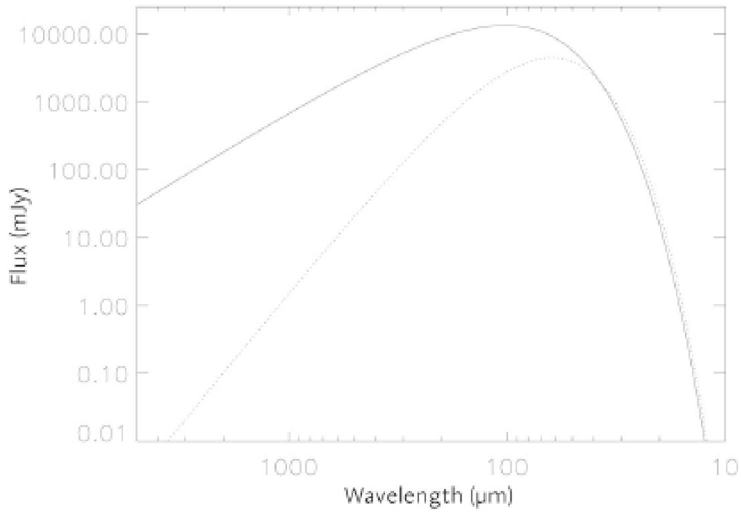


FIGURE 1 Comparison of flux emission between a blackbody (solid line) and a greybody (dotted line) for a fixed solid angle and temperature. Flux is given in units of milliJanskies, where 1 mJy = 10^{-29} W·m^{-2}·Hz^{-1}.

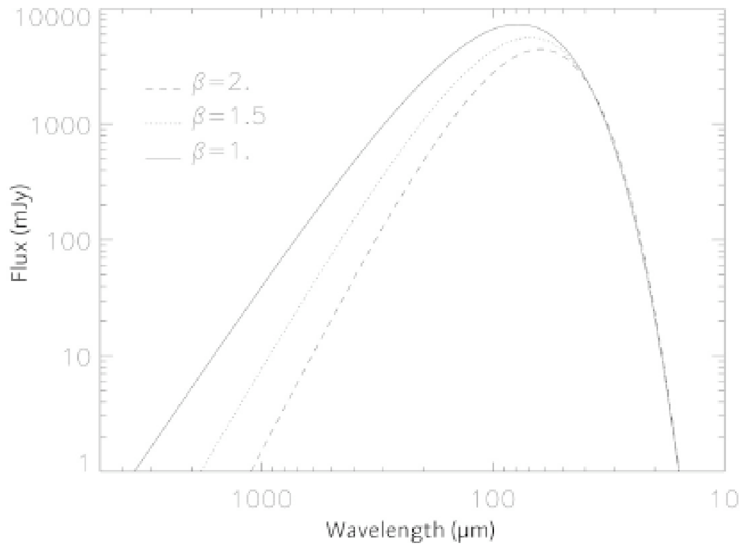


FIGURE 2 Greybody curve where β (unitless) is the varied parameter.

Radio Astronomy -
Polarized Dust Emission and Magnetic Field

- Measuring magnetic fields - dust continuum polarization
    - dust
        - continuum (emission/absorption; NOT scattered)
            - Linear polarization
            - due to alignment (see next page)
                - grain particles with magnetic moment (due to spinning) precess around the B-field
                - polarization provides the "direction" of B-field (perpendicular or parallel) "in" the plane of the sky
                - detail mechanism not secure
                - various competing processes including collision (temperature/density)

Radio Astronomy -
Polarized Dust Emission and Magnetic Field

- Dust continuum polarization mechanism
  - dust grain alignment (Lazarian, Goodman, Myers 1997, ApJ)

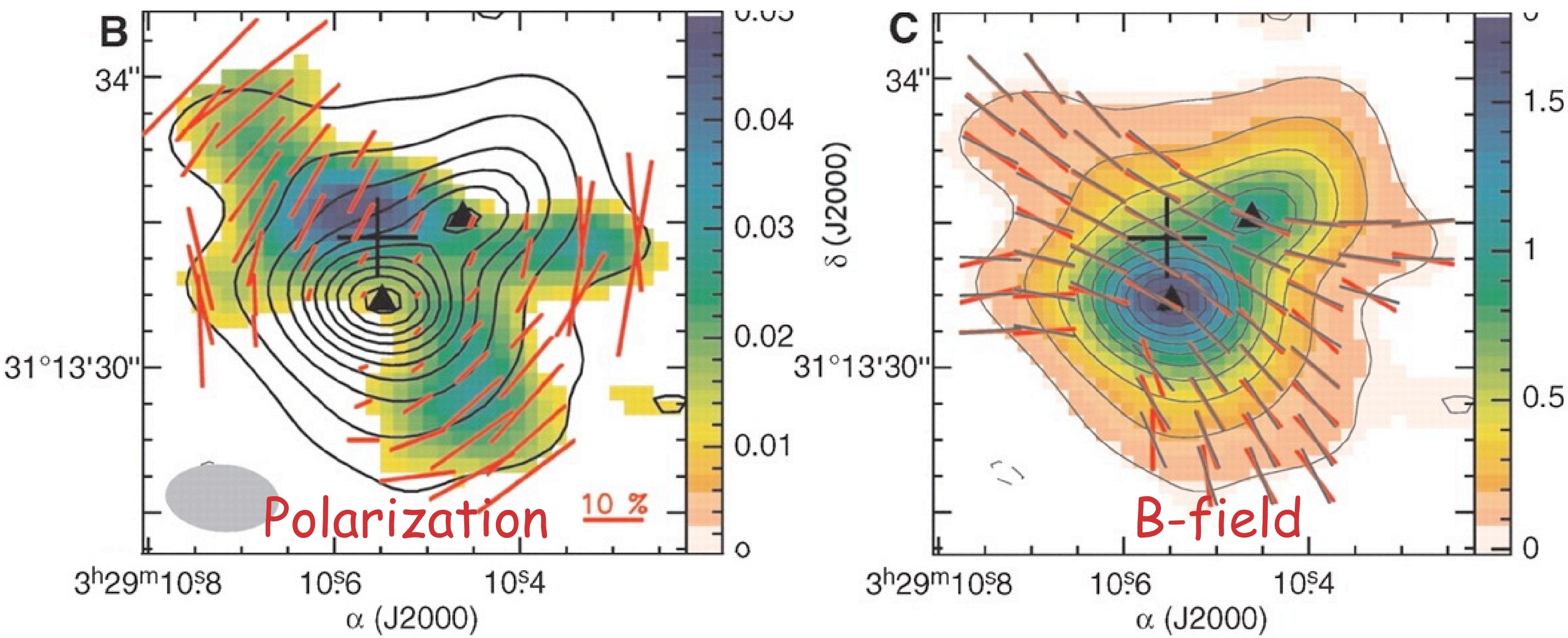
TABLE 1

MAJOR MECHANISMS OF GRAIN ALIGNMENT

Alignment Mechanism	Introduced	Description	Quantitative Theory	Special Conditions for Success
1. Gold	Gold 1951	Alignment of thermally rotating grains aligned by supersonic flows; *originally:* radiation pressure on grain; *further development:* Alfvénic waves (Lazarian 1994; Lazarian & Draine 1997b), ambipolar diffusion (Roberge et al. 1995)	Purcell 1969; Purcell & Spitzer 1971; Dolginov & Mytrophanov 1976; Lazarian 1994; Roberge et al. 1995; Roberge & Hanany 1990; Lazarian 1997a	Supersonic drift, rotation with thermal velocities
2. Mechanical alignment of suprathermally rotating grains	Lazarian 1995a	Alignment by suprathermally rotating grains by supersonic flows due to cross-section difference and due to gaseous bombardment during crossover events	Lazarian 1995a, 1995c; Lazarian & Efroimsky 1996; Lazarian, Efroimsky, & Ozik 1996	Supersonic drift, rotation with suprathermal velocities
3. Davis-Greenstein	Davis & Greenstein 1951	Alignment of thermally rotating grains through paramagnetic relaxation; *originally*: relaxation of paramagnetic grains; *further development*: relaxation of SPM grains (Jones & Spitzer 1967)	Jones & Spitzer 1967; Purcell & Spitzer 1971; Mathis 1986; Roberge et al. 1993; Lazarian 1995d; Lazarian & Roberge 1997a; Lazarian 1997b	Presence of SPM impurities
4. Purcell	Purcell 1975, 1979; Spitzer & McGlynn 1979	Alignment of suprathermally rotating grains through paramagnetic relaxation; *originally*: efficiency of alignment is limited for ordinary paramagnetic grains (Spitzer & McGlynn 1979); *further development:* incomplete Barnet relaxation enhances alignment (Lazarian & Draine 1997a)	Purcell 1979; Spitzer & McGlynn 1979; Lazarian 1995c, 1995e; Lazarian & Draine 1997a; Draine & Lazarian 1997a	Suprathermal rotation due to H_2 formation
5. Alignment by radiation torques	Draine & Weingartner 1996, 1997	Alignment due to the difference in scattering right and left polarized quanta	Draine & Weingartner 1996, 1997; Draine & Lazarian 1998	Radiation of short wavelength
6. Mechanical alignment of helical grains	Lazarian 1995b	Helical grains aligned by supersonic flows; atoms bounce off the grain surface of helical shape or off a grain with variation of the accommodation coefficient	Does not exist	Supersonic drift, special shape

Radio Astronomy -
Polarized Dust Emission and Magnetic Field

Radio Astronomy -
Polarized Dust Emission and Magnetic Field



Girart, Rao, & Marrone 2006

Hour glass shape of the magnetic field structure in the circumbinary envelope

The large scale field is well aligned with the minor axis and the mass-to-flux ratio is slightly over critical

BEST OBSERVATIONAL CASE SO FAR!!!

Radio Astronomy -
The Radio Sky

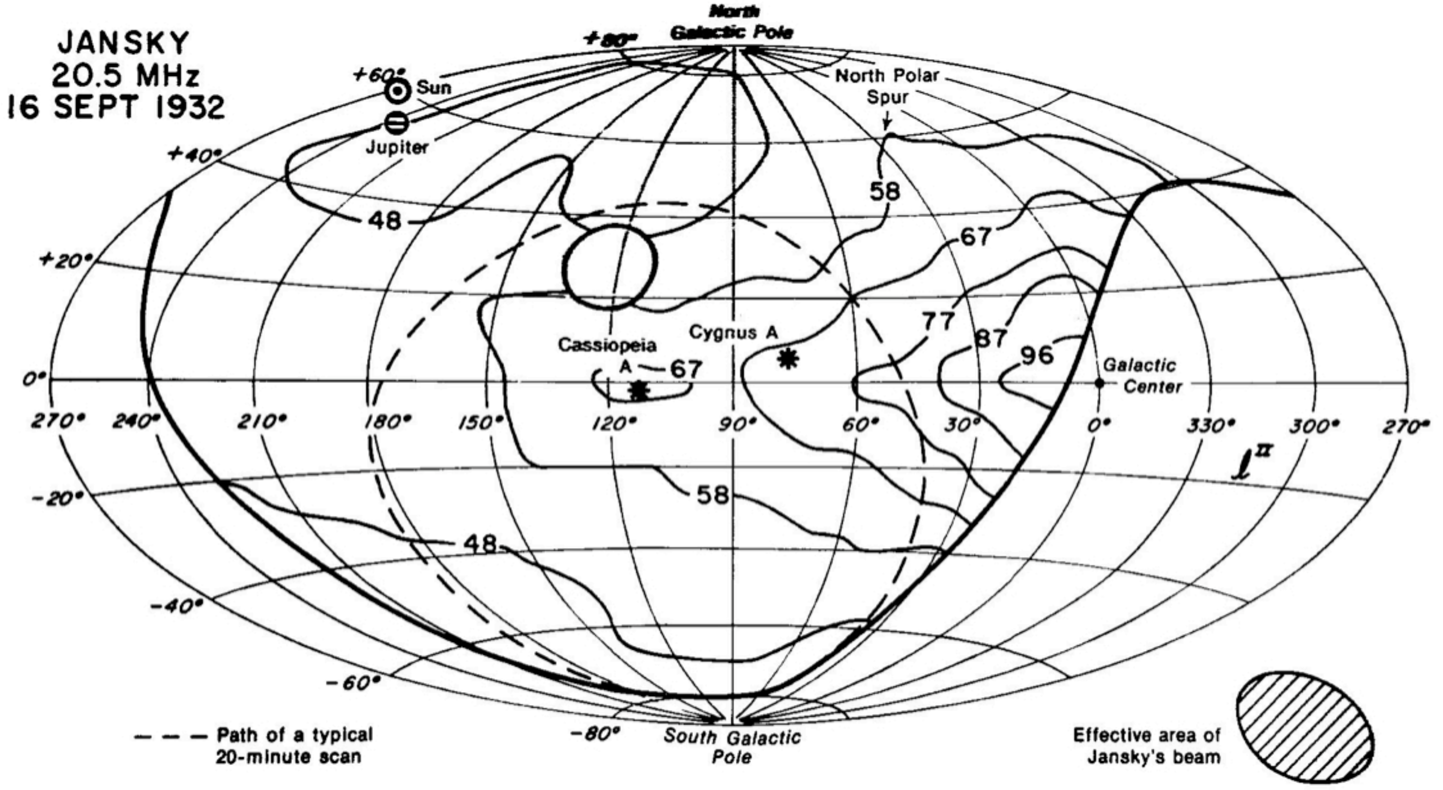


Fig. 1.1. A modern reduction of Jansky's data taken on 16 September 1932 (after Sullivan 1978). The contour map is in galactic coordinates in which 0° latitude corresponds to the plane of the Milky Way and 0° longitude corresponds to the galactic center. Contours are labeled in 1000 K.

Radio Astronomy -
The Radio Sky

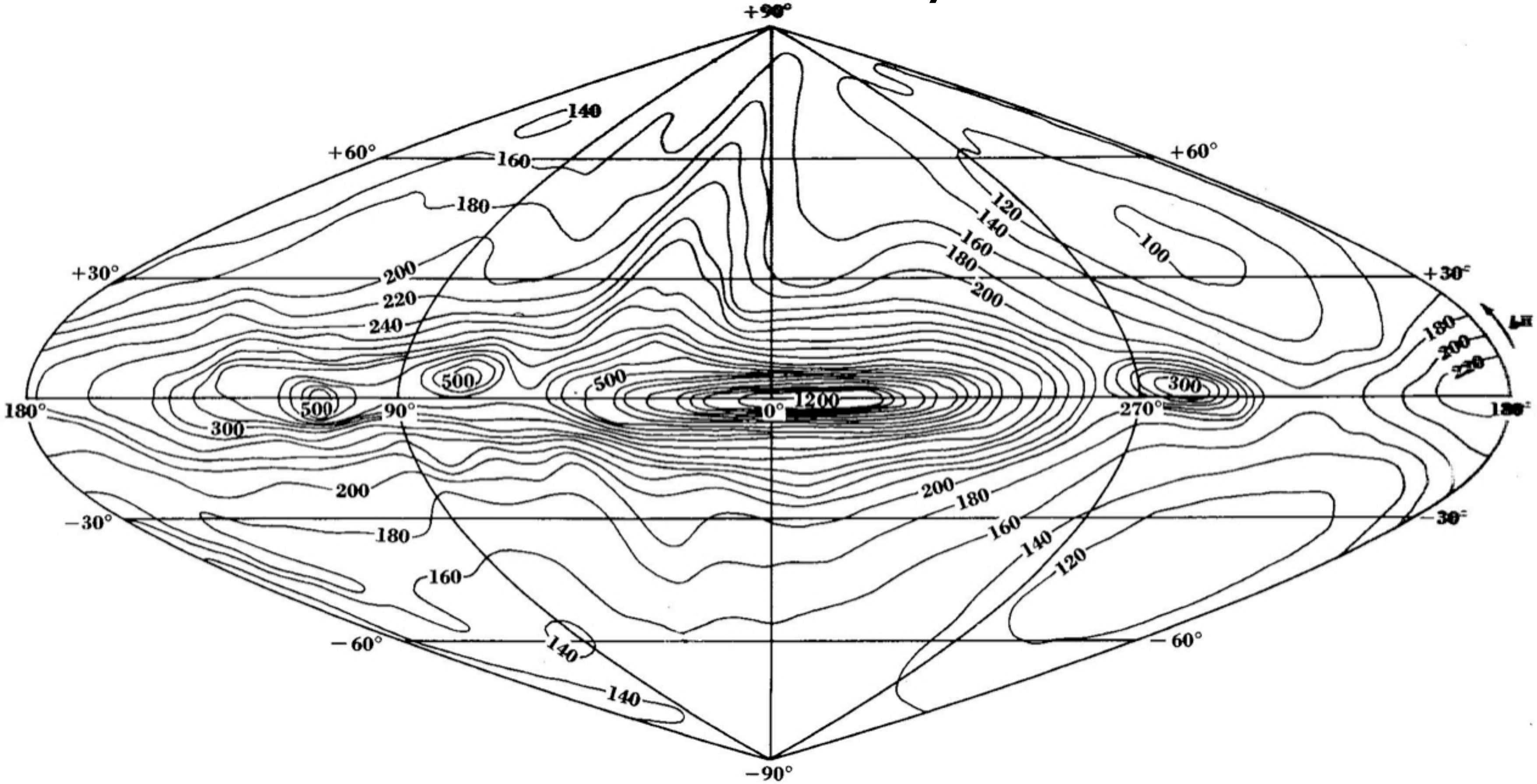
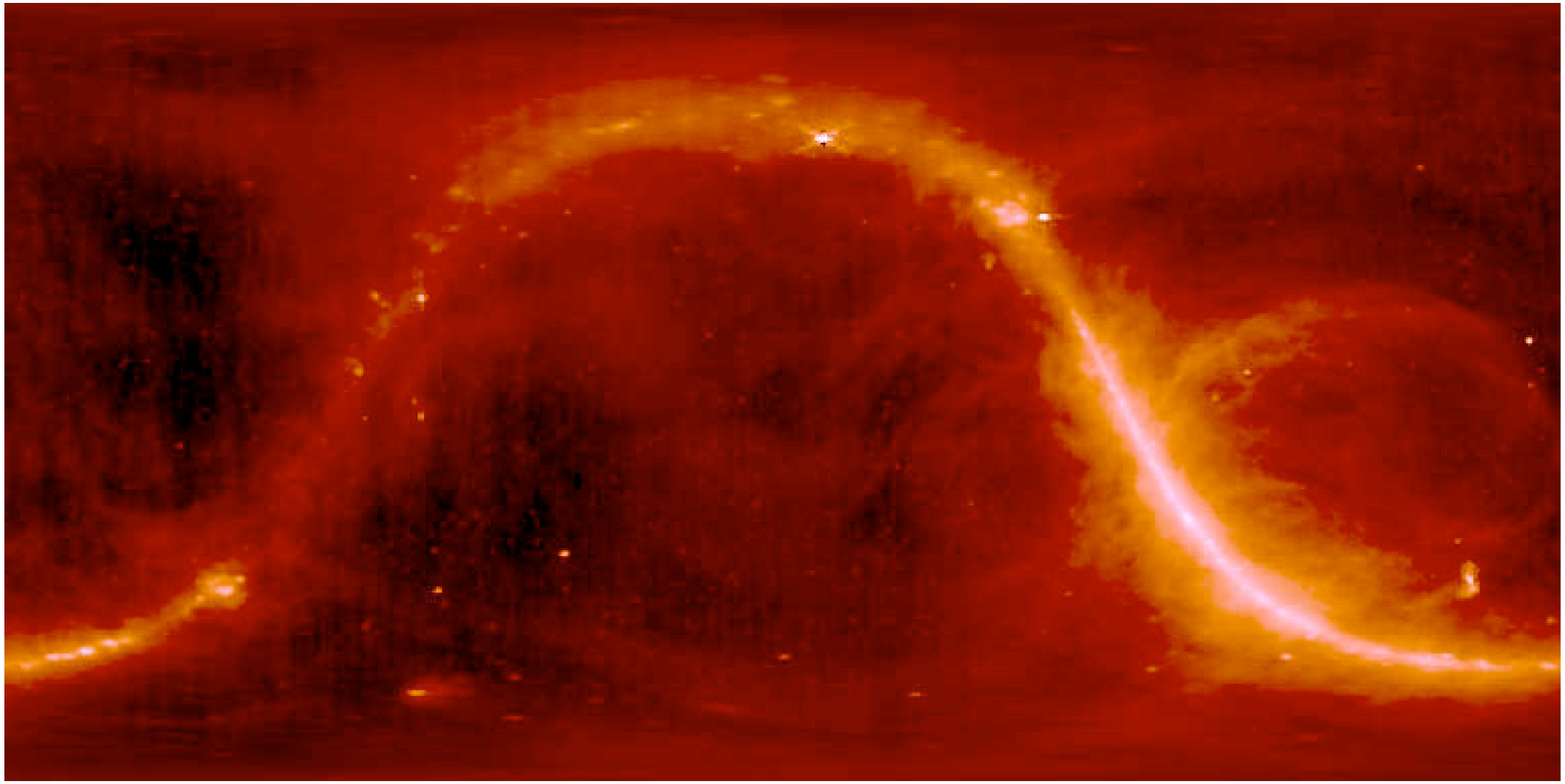


Fig. 1.2. A low-resolution (beam 17° × 17°) map of the distribution of brightness temperature at 200 MHz (Droge and Priester 1956).

Radio Astronomy -
The Radio Sky



Radio Astronomy -
The Radio Sky

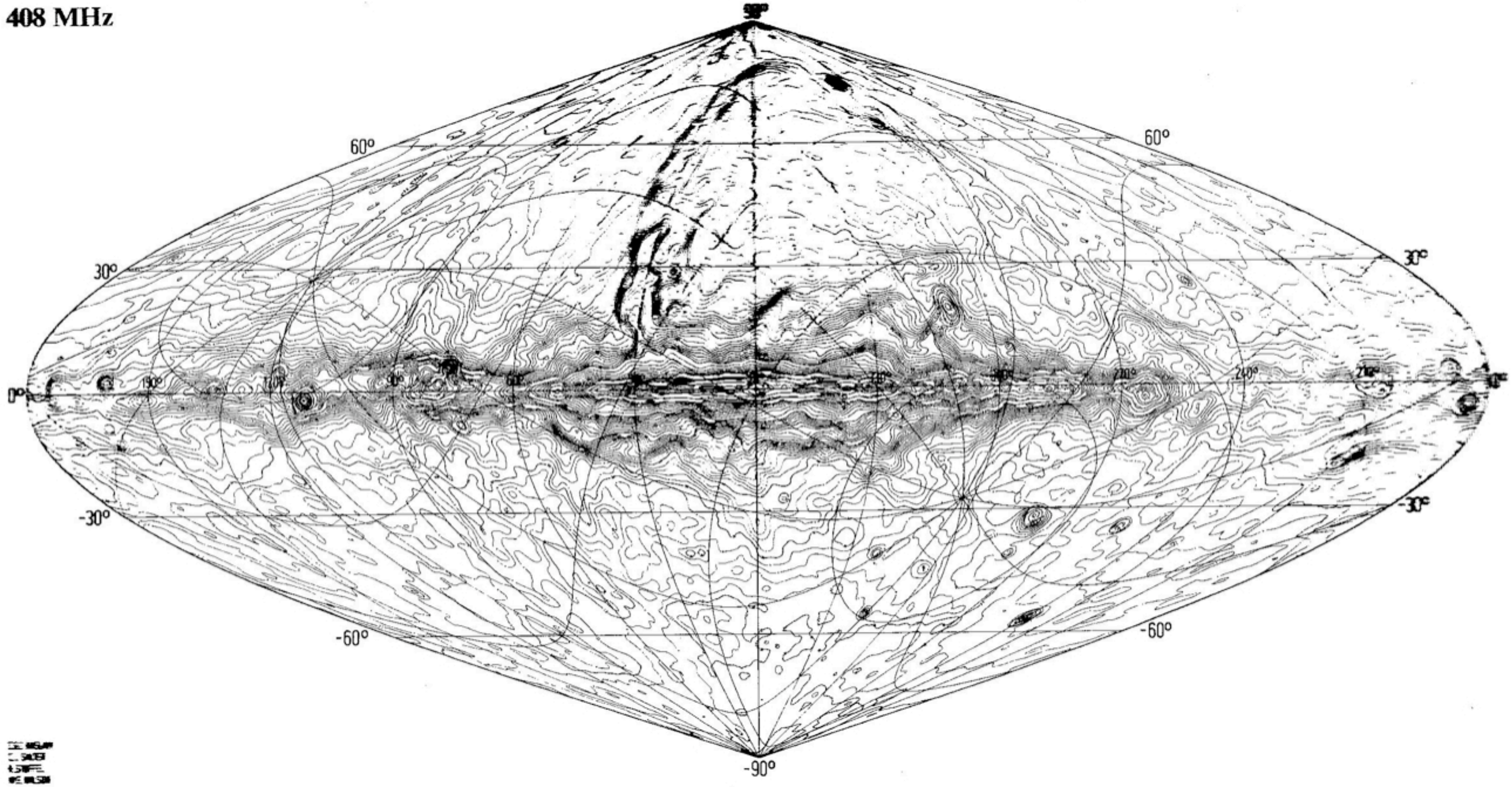
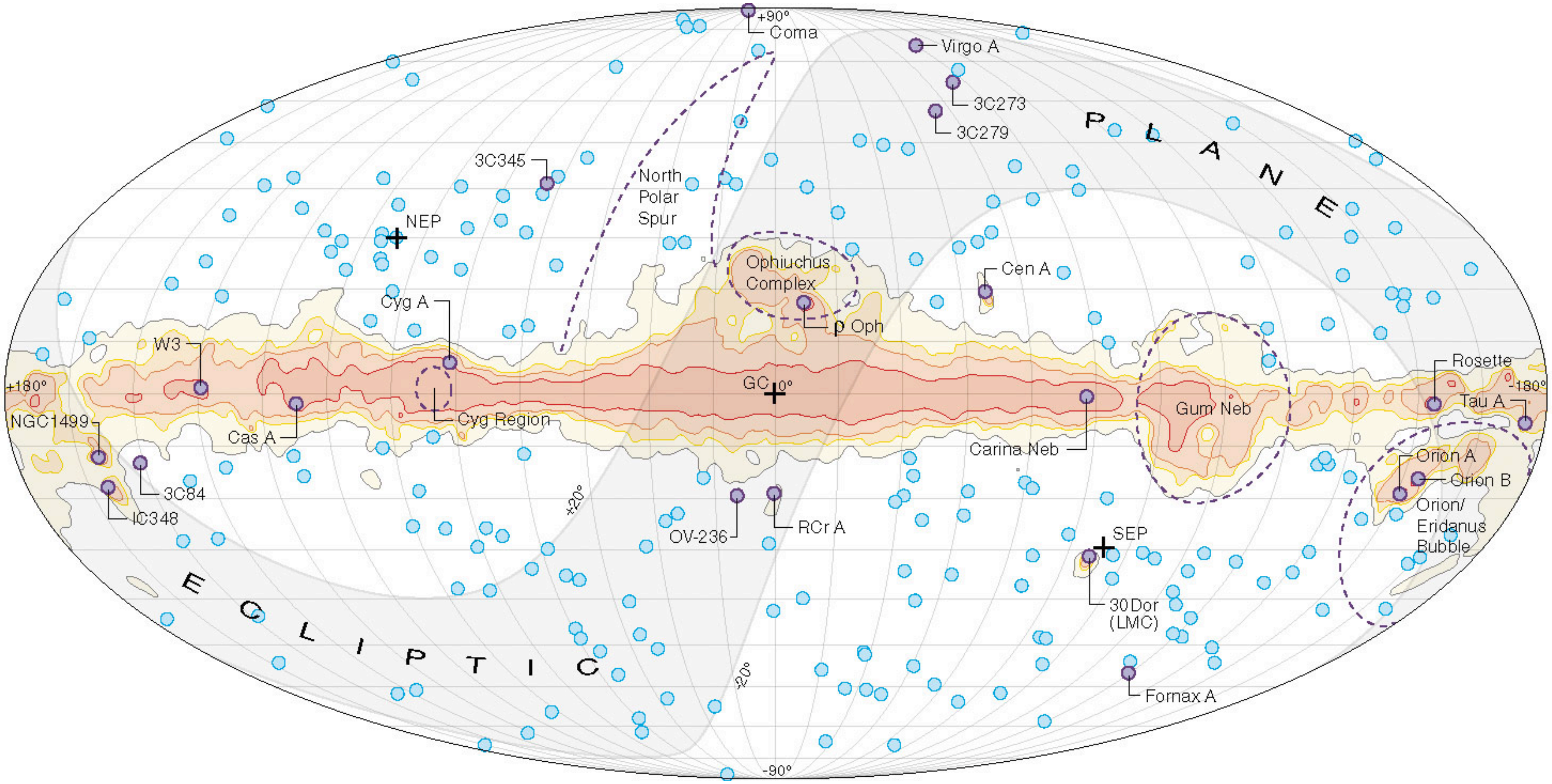


Fig. 1.5. The all-sky map at 408 MHz presented by Haslam et al. (1982).

Radio Astronomy -
The Radio Sky

- Microwave Sky



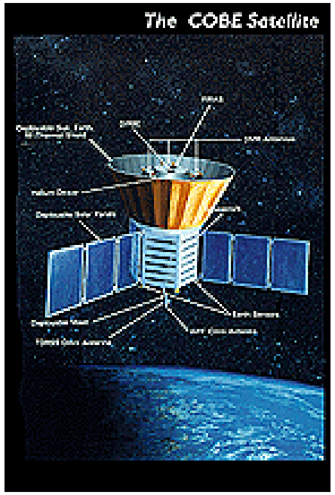
Radio Astronomy - CMB

- CMB
  - topics
    - anisotropy (power spectrum)
    - polarization
    - SZ Effect
  - experiments (e.g. http://cfa-www.harvard.edu/~mwhite/cmbexptlist.html)

experiment	type	freq(GHz)	Scale(l)
COBE	space	30-90	2-30
Boomerang	balloon	90-420	10-700
MAXIMA	balloon	150-420	50-700
CBI	ground	26-36	300-3000
DASI	ground	26-36	125-700
WMAP	space	22-90	2-1000
AMiBA	ground	70-90(?)	SZ
SZA	ground	30-90	SZ
Plank	space	30-850	2-2000

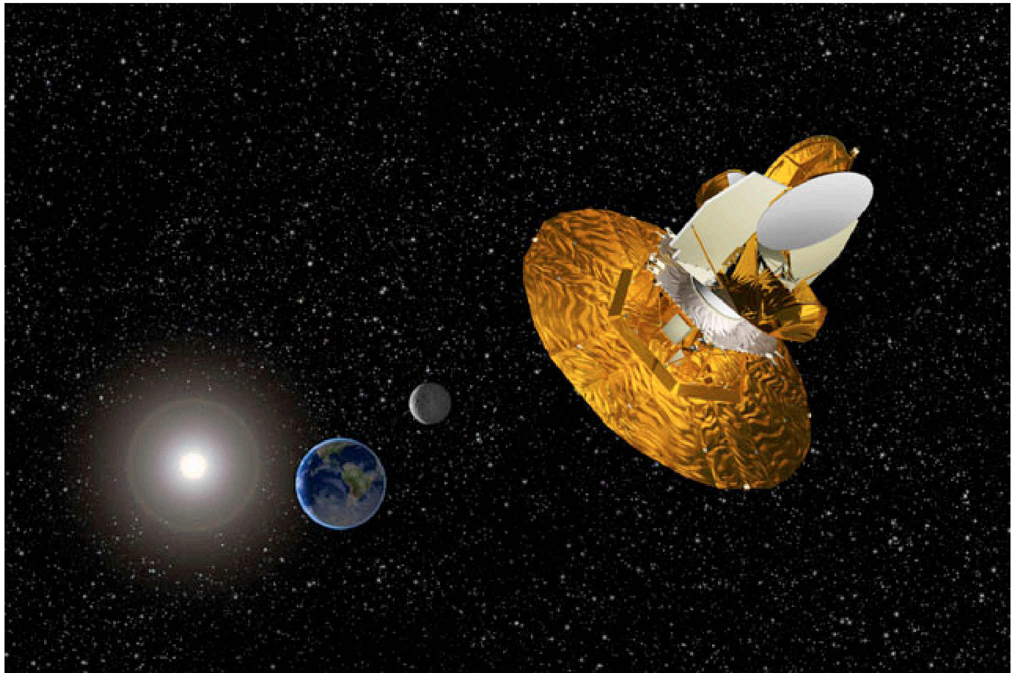
Radio Astronomy - CMB

- CMB experiments
  - space satellites



COBE

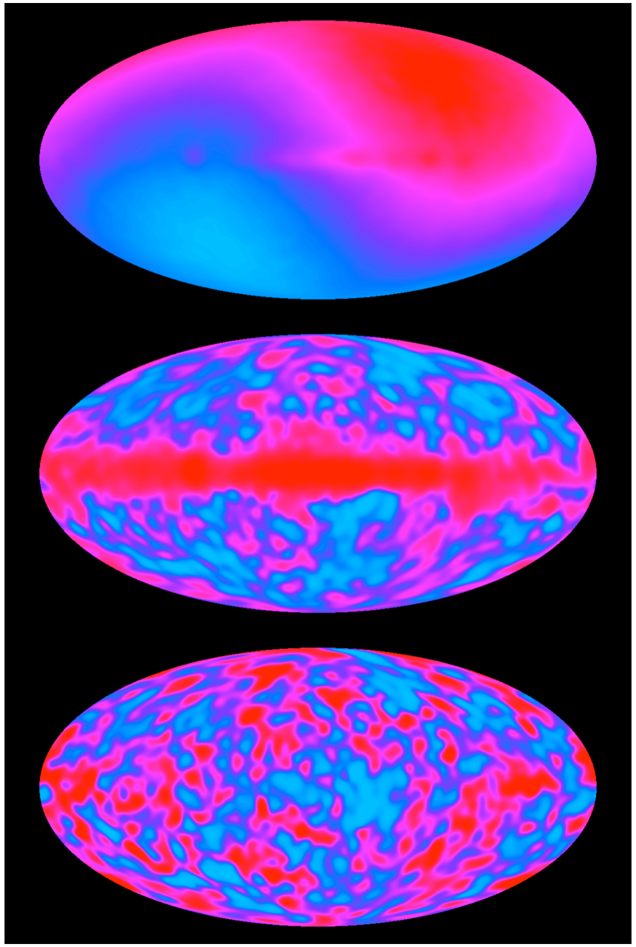
WMAP



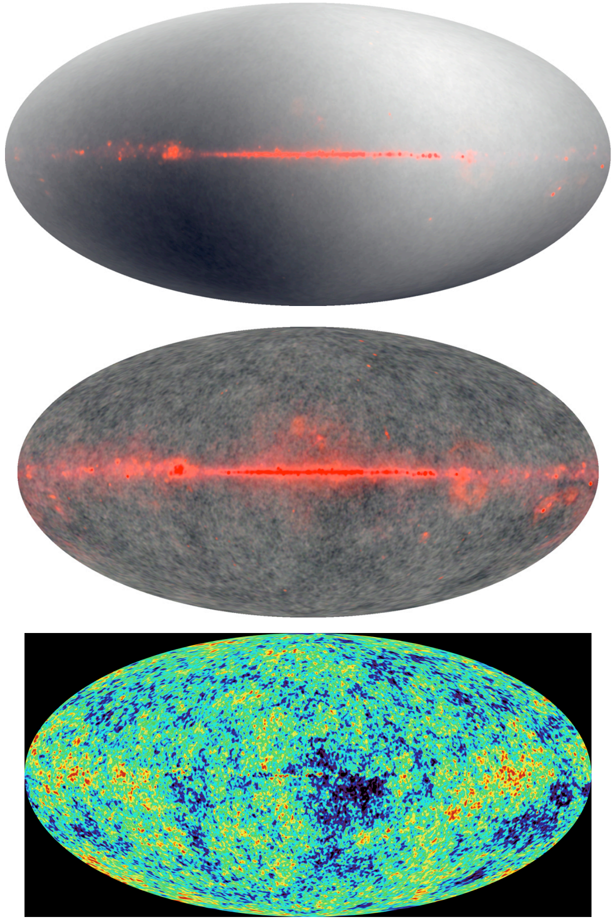
Radio Astronomy - CMB

- CMB experiments

COBE

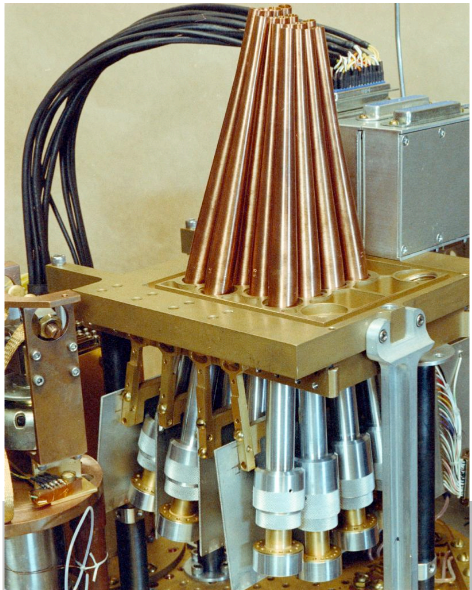


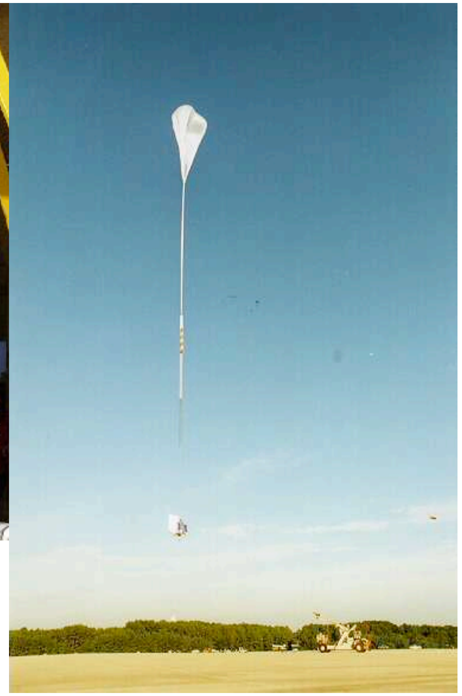
WMAP



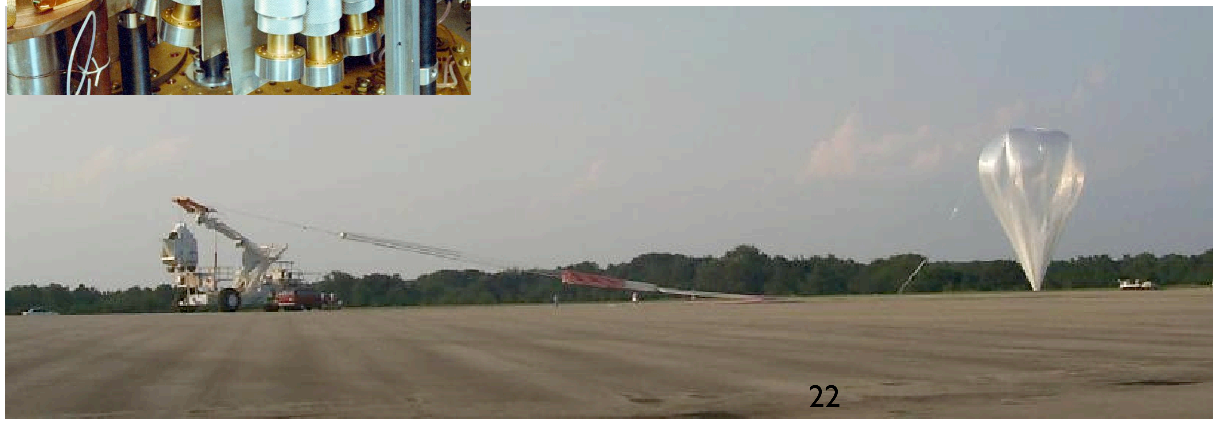
Radio Astronomy - CMB

- CMB experiments
  - balloons





MAXIMA



Boomerang

Radio Astronomy - CMB

- CMB experiments
  - ground

DASI

CBI

SZA

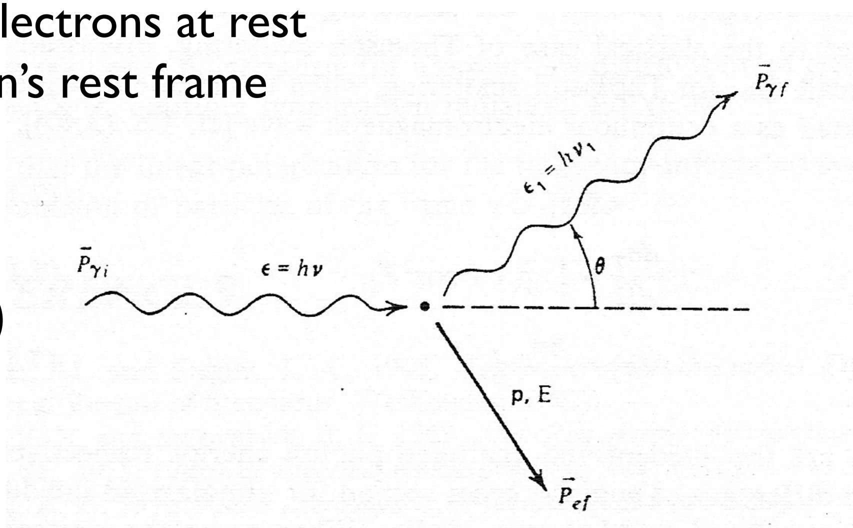
Radio Astronomy - CMB

- References
  - Birkinshaw 1999, Physics Reports
    "The Sunyaev-Zel'dovich Effect"
  - Carlstrom 2002, ARA&A, 40, 643
    "Cosmology with the Sunyaev-Zel'dovich Effect"
- Thomson scattering
  - photon scattering off electrons at rest
  - $h\nu \ll m_e c^2$ in electron's rest frame

$$\varepsilon = \varepsilon_1$$

$$\frac{d\sigma_T}{d\Omega} = \frac{1}{2} r_0^2 (1 + cos^2\theta)$$

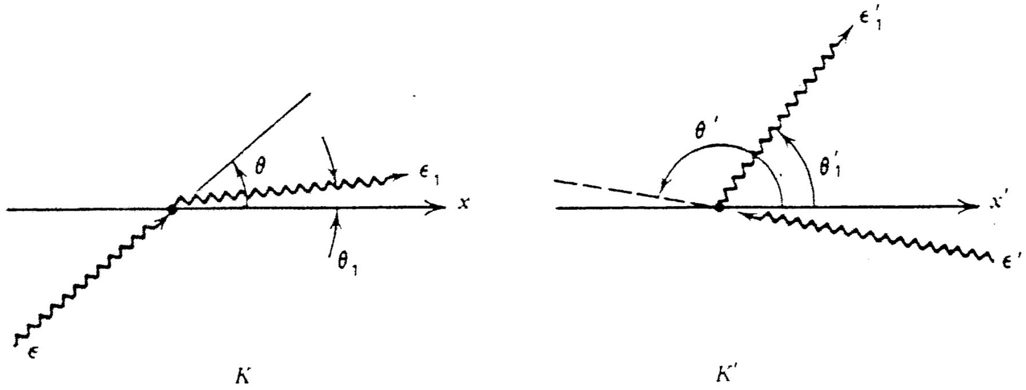
$$\sigma_T = \frac{8\pi}{3} r_0^2$$



Radio Astronomy - CMB

- References
  - Birkinshaw 1999, Physics Reports
    "The Sunyaev-Zel'dovich Effect"
  - Carlstrom 2002, ARA&A, 40, 643
    "Cosmology with the Sunyaev-Zel'dovich Effect"
- Inverse Compton Scattering
  - photon scattering off electrons in motion
  - $h\nu \ll m_e c^2$ in electron's rest frame still

$$\varepsilon_1 = \frac{\varepsilon}{1 + \frac{\varepsilon}{mc^2}(1 - cos\theta)}$$



Radio Astronomy - CMB

- Inverse Compton Scattering
  - with relativistic electrons

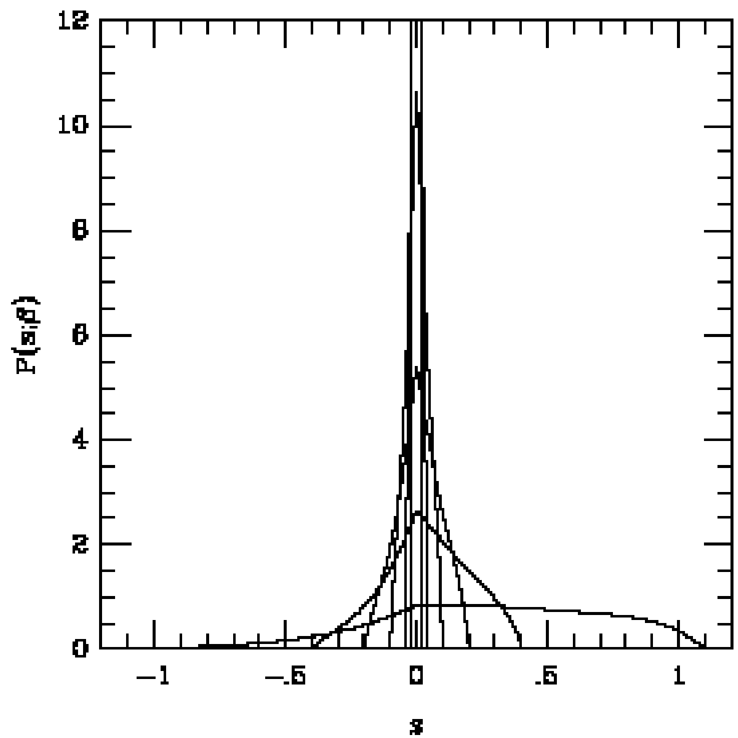


Fig. 4.— The scattering probability function $P(s;\beta)$, for $\beta = 0.01$, 0.02, 0.05, 0.10, 0.20, and 0.50. The function becomes increasingly asymmetric and broader as β increases.

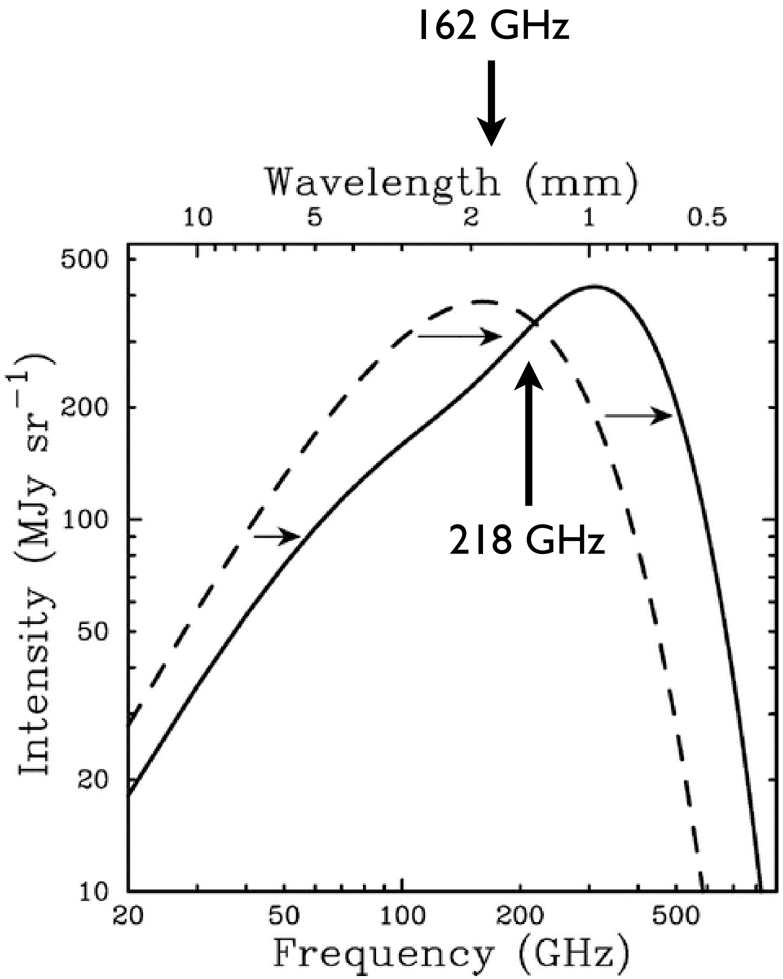
Radio Astronomy - CMB

- Sunyaev-Zel'dovich effect
  - Sunyaev & Zel'dovich (1970)
  - CMB photons interact with 10^8K plasma in clusters, typically extend on the Mpc scale (angular size of several arcmins)
  - no confirmed results until late 1990's

$$\frac{\Delta T}{T} = \frac{2kT_e}{m_e c^2}\, \sigma_T\, N_e\, L$$

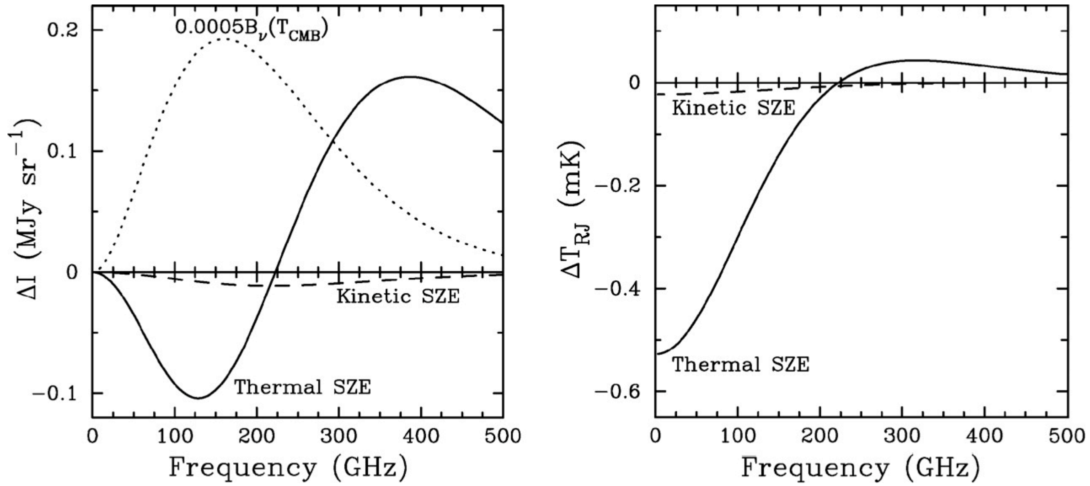
$$\sigma_T = \frac{8\pi}{3}\left(\frac{e^2}{m_e c^2}\right)^2 = 6.65\ 10^{-25} cm^{-2}$$

$$= 2.24\ 10^{-34}\ T_e\, N_e\, L$$



Radio Astronomy - CMB

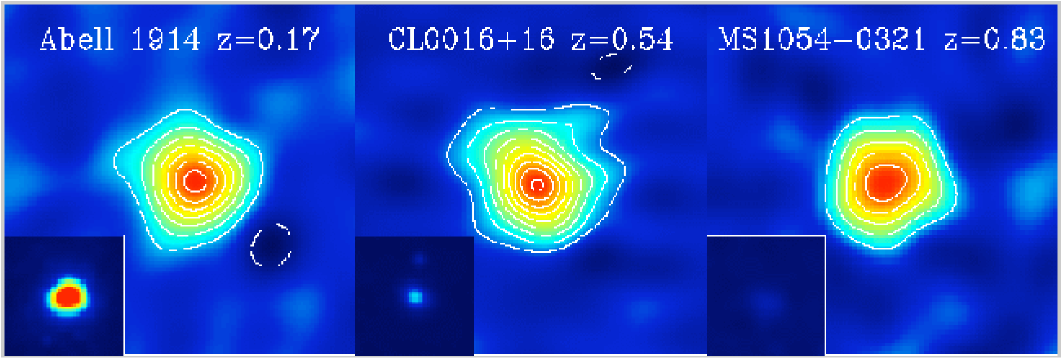
- Sunyaev-Zel'dovich effect
  - thermal SZ effect
  - kinetic SZ effect



- Observational concerns, e.g.
  - contamination from various foreground sources such as extragalactic synchrotron (low freq.), galactic f-f (low freq.), thermal dust(high freq)

Radio Astronomy - CMB

- Sunyaev-Zel'dovich effect
  - pros and cons
    - extended low surface brightness
    - sensitive to massive objects, i.e. clusters of galaxies
    - independent of red-shifts



  - bias toward massive objects but unbiased to z (distance)
  - SCIENCE!
    - (with X-ray data) an independent measure of H_0 from other by using standard candles
    - structure formation through (unbiased) cluster survey

Radio Astronomy - CMB

- Sunyaev-Zel'dovich effect

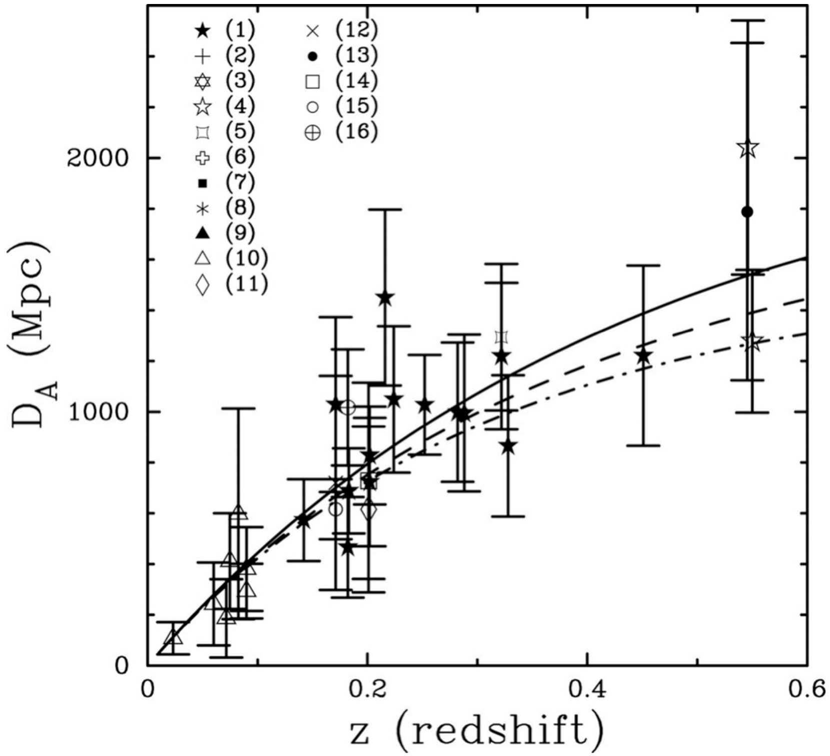
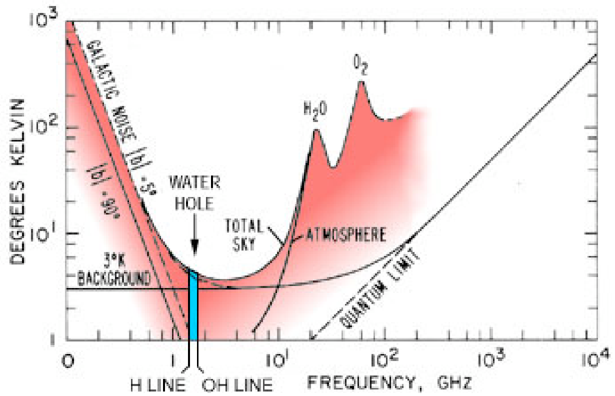


Figure 9 SZE-determined distances versus redshift. The theoretical angular diameter distance relation is plotted for three different cosmologies, assuming $H_0 = 60$ km s^{-1} Mpc^{-1}. $\Omega_M = 0.3$, $\Omega_\Lambda = 0.7$ (*solid line*), $\Omega_M = 0.3$, $\Omega_\Lambda = 0$ (*dashed line*), and $\Omega_M = 1.0$, $\Omega_\Lambda = 0$ (*dot-dashed line*). The clusters are beginning to trace out the angular diameter distance relation. References: (1) Reese et al. 2002; (2) Pointecouteau et al. 2001; (3) Mauskopf et al. 2000a; (4) Reese et al. 2000; (5) Patel et al. 2000; (6) Grainge et al. 2000; (7) Saunders et al. 2000; (8) Andreani et al. 1999; (9) Komatsu

The Search for ExtraTerrestrial Intelligence, SETI

- Brief early history
  - 1959 - Cocconi and Morrison : the potential of using microwave radio for communicating between the stars
  - 1960 - Drake started using the 85-foot West Virginia antenna at NRAO in searching toward two nearby stars suggested by the agove authors
  - 1960's - Soviet Union
  - 1971 - NASA Ames with concept study Project Cyclops
  - late 1970's - NASA Ames (targeted search) and JPL (all sky survey)
  - 1988 - NASA SETI funded
  - 1992 - NASA SETI began
  - 1993 -NASA SETI terminated

- Approach
  - best penetration - radio
  - channel with low background - 1.4-1.62 GHz
  - signal type -
    - broadband leakage
    - narrow band targeted



The Search for ExtraTerrestrial Intelligence, SETI

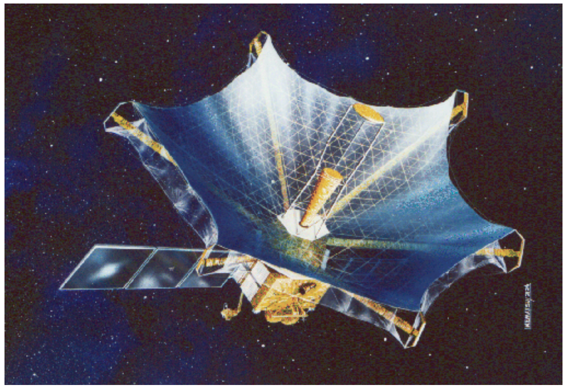
- Ongoing projects
  - SETI Institute
    - Project Phoenix
    - Optical SETI
    - ATA
  - Ohio State Big Ear
  - SERENDIP
  - Southern SERENDIP
  - SETI Italia
  - Project BAMBI
  - Optical SETI at
    - Columbus
    - Berkeley
    - Harvard
  - SETI@Home

The Search for ExtraTerrestrial Intelligence, SETI

- The Drake equation
  - presented by Frank Drake in 1961
  - $N = R_{*} f_p n_e f_l f_i f_c L$
    - N: The number of civilizations in the Milky Way whose electromagnetic emissions are detectable
    - R_{*} : the rate of formation of stars suitable for the development of intelligent life
    - f_p: the fraction of those stars with planetary systems
    - n_e: the number of planets, per solar system, with an environment suitable for life
    - f_l: the fraction of suitable planets on which life actually appears
    - f_i: the fraction of life bearing planets on which intelligent life emerges
    - f_c: the fraction of civilizations that develop a technology that releases detectable signs of their existence into apace
    - L: the length of time such civilizations release detectable signals into space

Radio Astronomy - Modern Telescopes

- Better FE (Receivers and Amplifiers) and BE (correlators), Combined Telescopes
  - e.g. eVLA, eVLBI, CARMA (BIMA+OVRO), SMA-JCMT-CSO
  - receiver development
    - TeraHertz, high frequency band
    - Wideband bolometers as well as hyterodyne systems
    - focal plan arrays
- Bigger dishes - mechanically challenging
  - e.g. LMT
- More Dishes - electronically challenging
  - e.g. ATA, ALMA, SKA
- Better Sites
  - RFI- radio frequency interference
  - More space missions?



Final Remarks

- What you should have learned by now
- technical side
  - luminosity, flux, flux density, intensity, temperature
- science side
  - characteristic signatures of different known emission mechanism
  - what radio observations can and may offer to tackle astrophysical (and astrochemical/"astrobiological") problems

- What we did not have a chance to talk about
  - many, but to name a few
    - technical side
      - FE/BE in general
      - non-LTE line excitation
    - science side
      - solar system (e.g. the Sun, asteroids)
      - stellar radio astronomy (e.g. flare stars, ionized stellar wind, novae, pulsars...)
      - molecular contents/chemistry in clouds