ISM Structure

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Milky Way ISM Overview

- ISM confined to thin gaseous disk.
- Thickness ~500 pc.
    - Sun at 8.5 kpc from center.

Milky Way from Cobe

http://messier.seds.org/more/mw_cobe.html

Milky Way ISM Overview

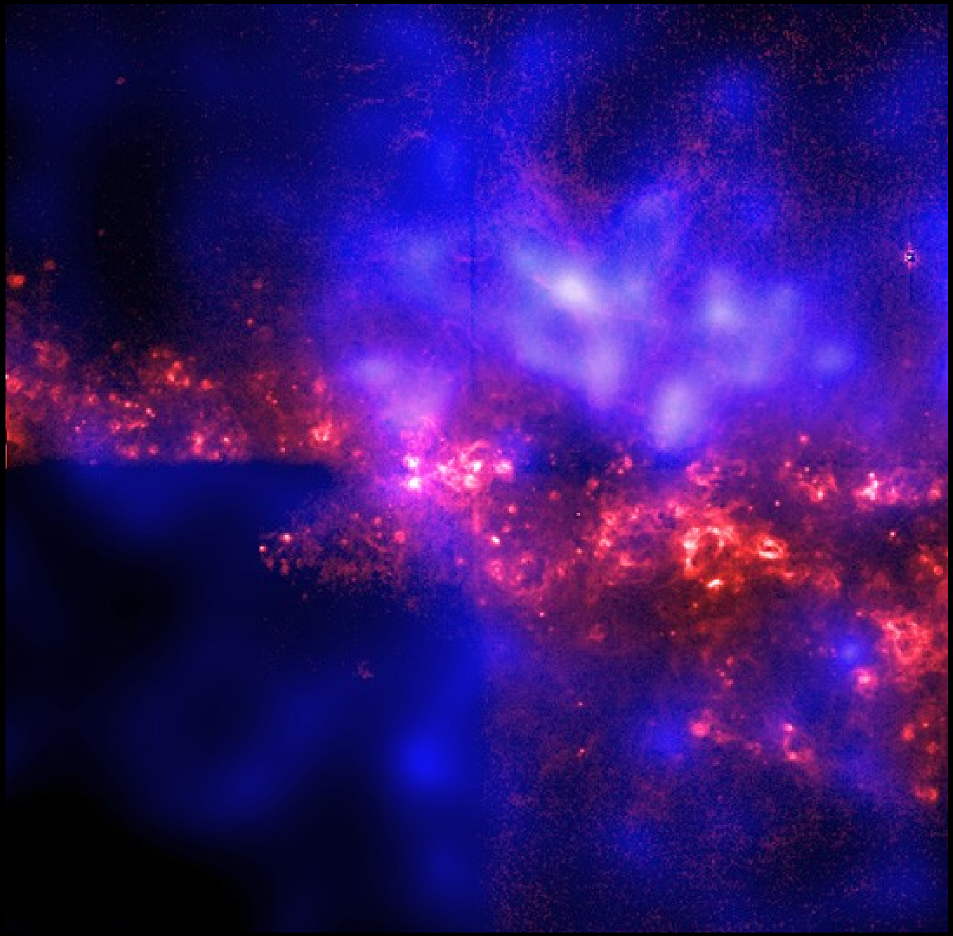
- Mass of MW within 15 kpc of center:
    - total: 10^{11} $M_\odot$.
    - stars: 5×10^{10} $M_\odot$.
    - dark matter: 5×10^{10} $M_\odot$.
    - ISM: 7×10^{9} $M_\odot$.

Milky Way from Cobe

http://messier.seds.org/more/mw_cobe.html

Phases of the ISM

- Coronal gas (HIM)
  - Filling factor > 0.5.
  - Density ~ 0.001 cm^{-3}.
  - T > $10^{5.5}$ K.
- Heating from supernova explosions.
- Collisionally ionized.

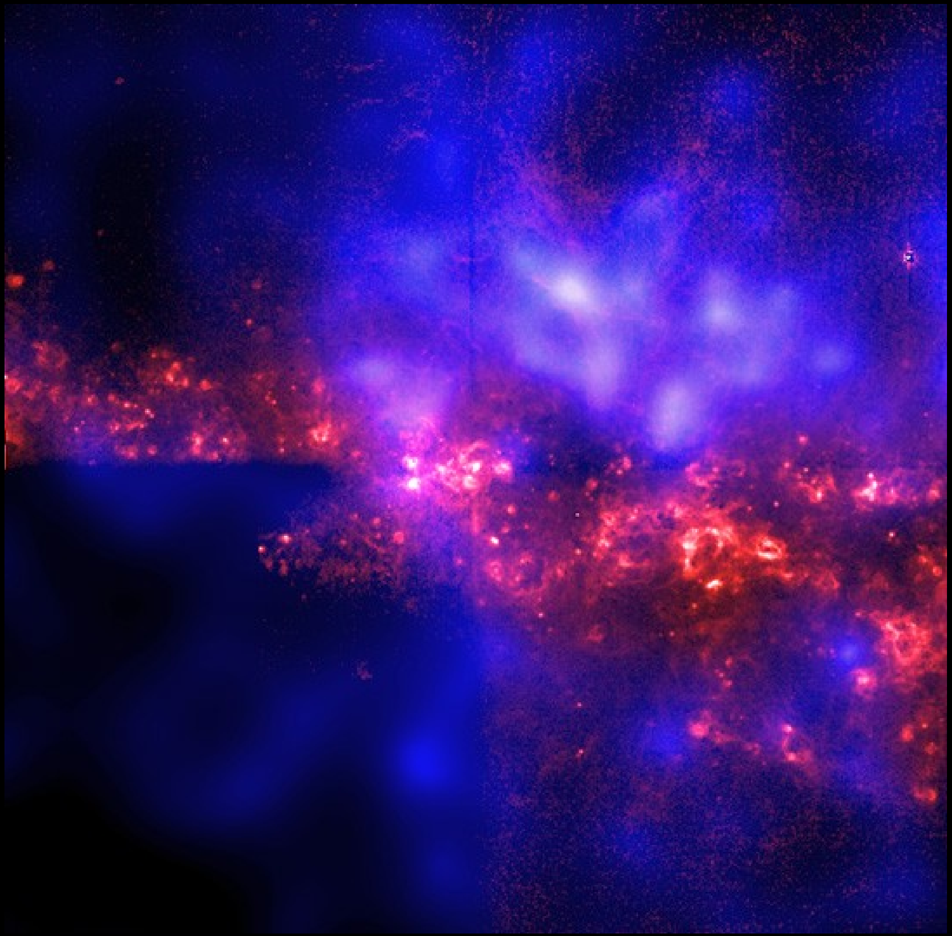


NGC 4631

http://imagine.gsfc.nasa.gov/docs/features/news/01aug01.html

Phases of the ISM

- Coronal gas (HIM)
- Cooling by:
  - Adiabatic expansion.
  - X-ray emission.
- Observations:
  - Line emission in X-rays and O VI.
  - Continuum synchrotron emission in radio.



Chandra observations of NGC 4631

http://imagine.gsfc.nasa.gov/docs/features/news/01aug01.html

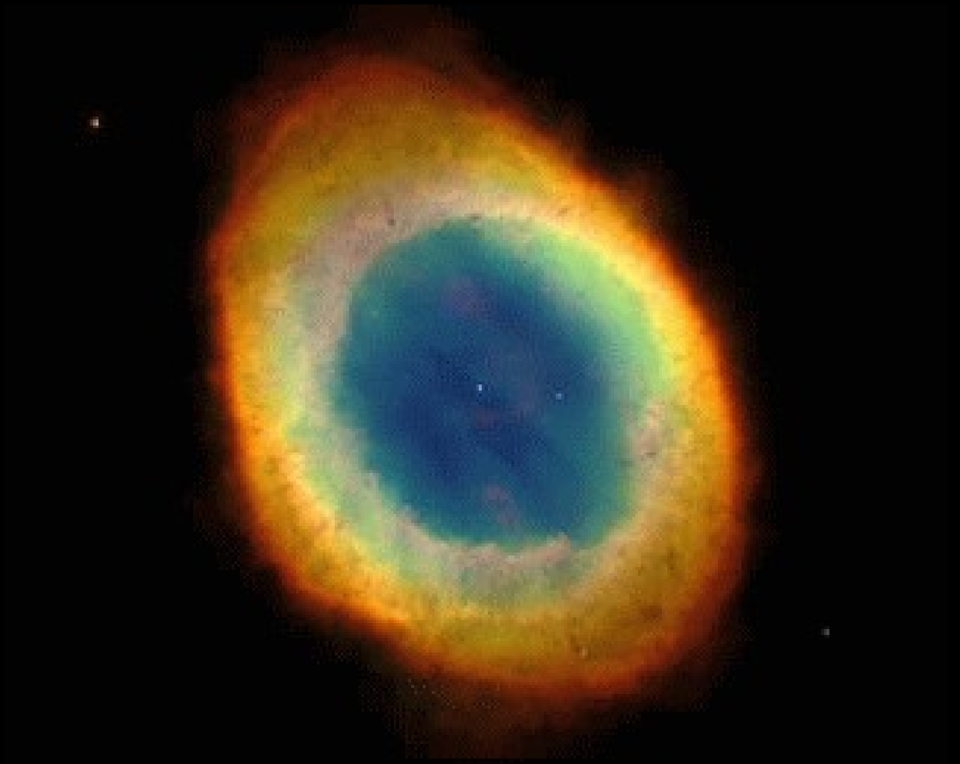
Ionized Gas

- Ionized H II regions.
  - $f \sim 0.1$.
  - $n_H = 0.02\ cm^{-3}$.
  - $T \sim 10{,}000$ K.
- Either diffuse ISM (WIM) or bright H II regions.
- Photoionized; heating from electrons.

http://monicks.net/2010/06/29/astronomy-picture-of-the-day-the-dark-tower-in-scorpius/

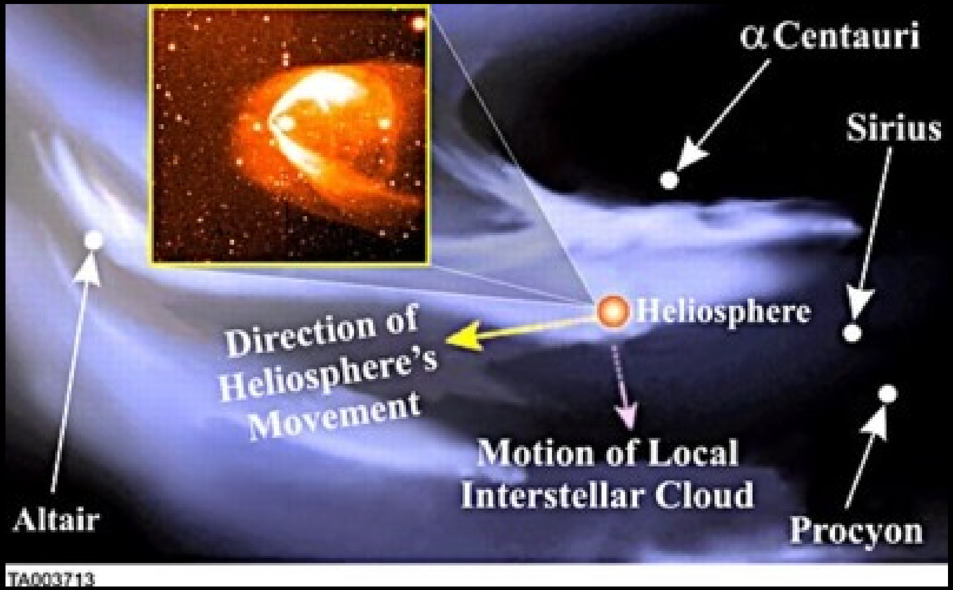
Ionized Gas

- Cooling by:
  - Line emission including fine structure.
  - Free-free emission.
- Observed:
  - Optical line emission (Balmer emission).
  - Thermal radio continuum.



Warm Neutral Gas

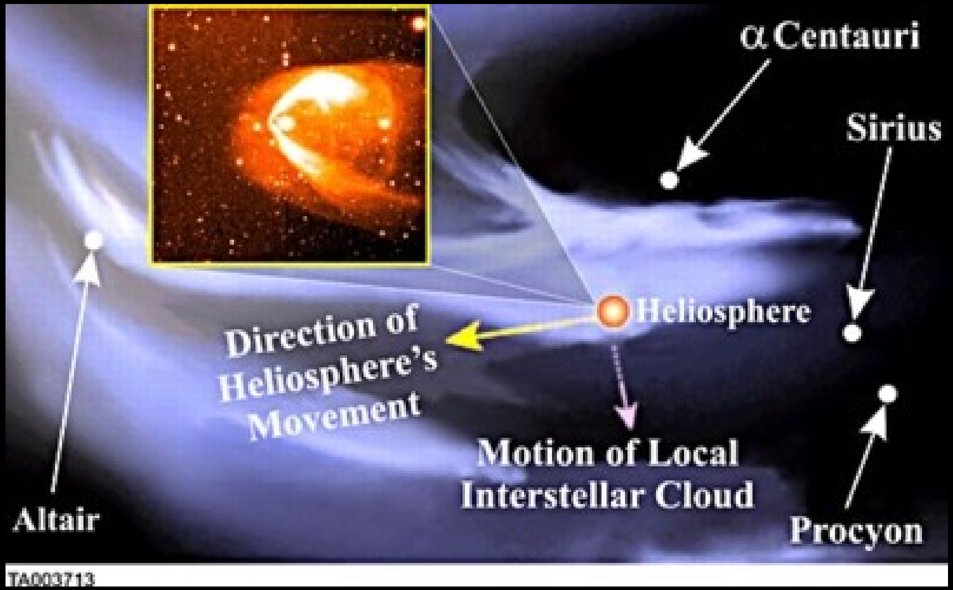
- Neutral hydrogen
    - $f = 0.1$
    - $n_H = 0.2\ cm^{-3}$
    - $T = 5000\ K$
- Heating from electrons; starlight.



http://www.centauri-dreams.org/?p=681

Warm Neutral Gas

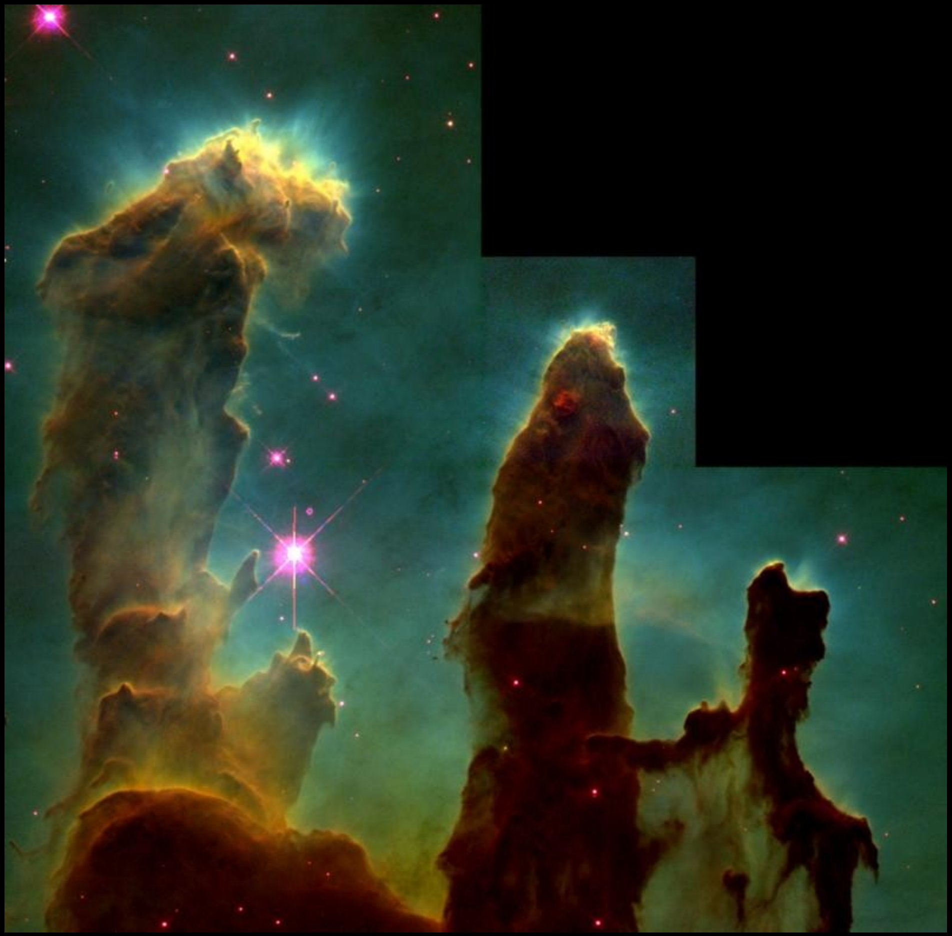
- Cooling by line emission.
- Observed through:
    - 21 cm emission/absorption.
    - UV/optical absorption lines.



http://www.centauri-dreams.org/?p=681

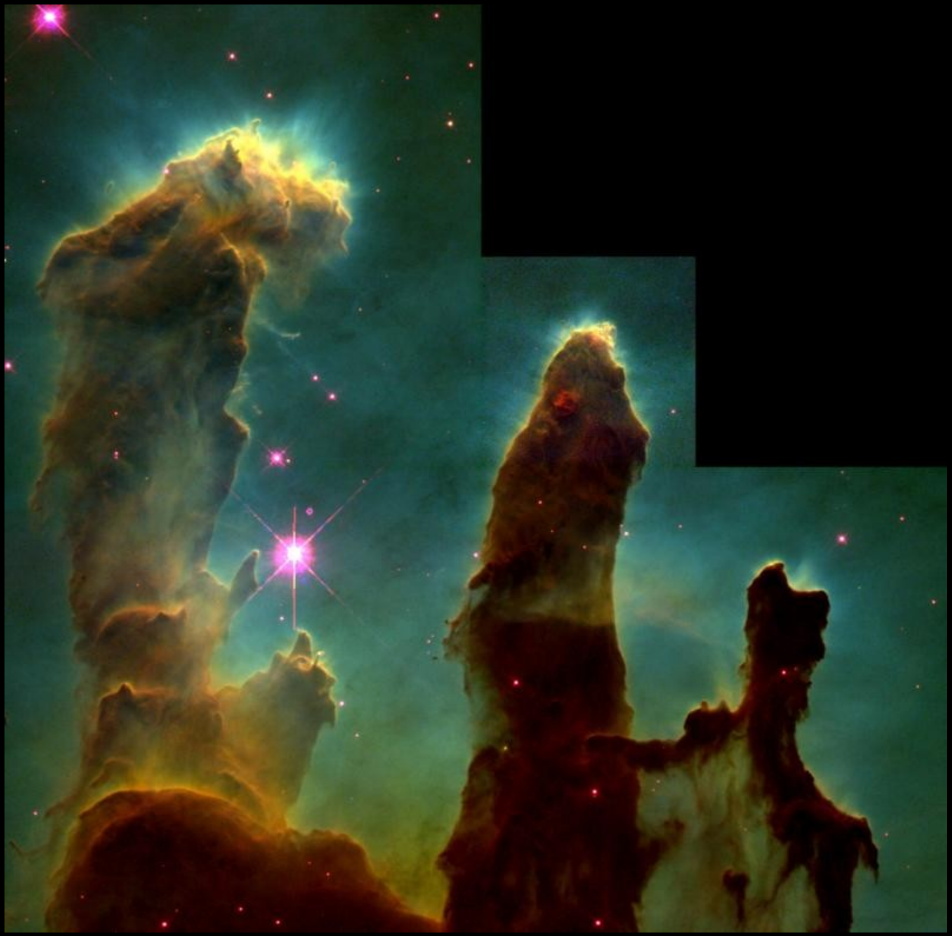
Cold Gas

- Cold neutral medium
    - $T = 100$ K
    - $nH = 30$ cm^{-3}
    - $f = 0.01$
- Heating by photo-electrons from dust.
- Cooling by line emission.
- Observed through 21 cm and UV/optical lines.



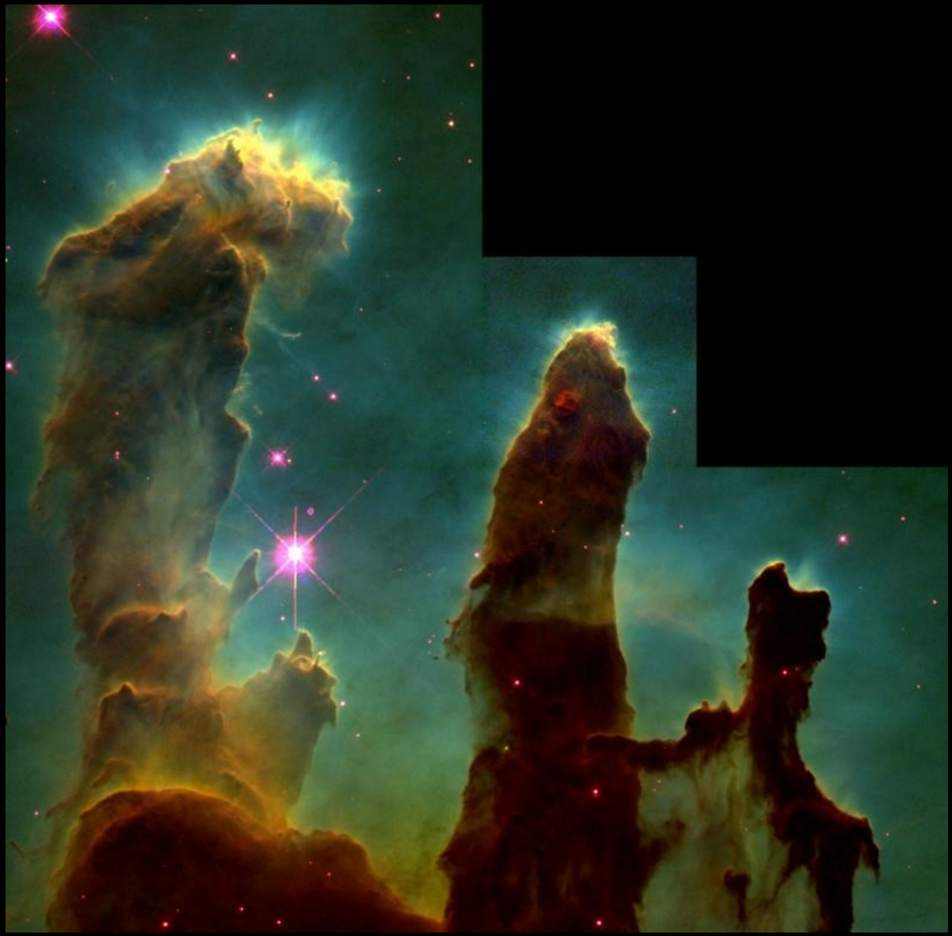
Cold Gas

- Diffuse H_2:
  - $f = 0.001$
  - $n_H = 100\ cm^{-3}$
  - $T = 100\ K$
- Protected against disassociation by H I.
- Cooling from fine structure lines.
- Observed through absorption lines/ CO emission.

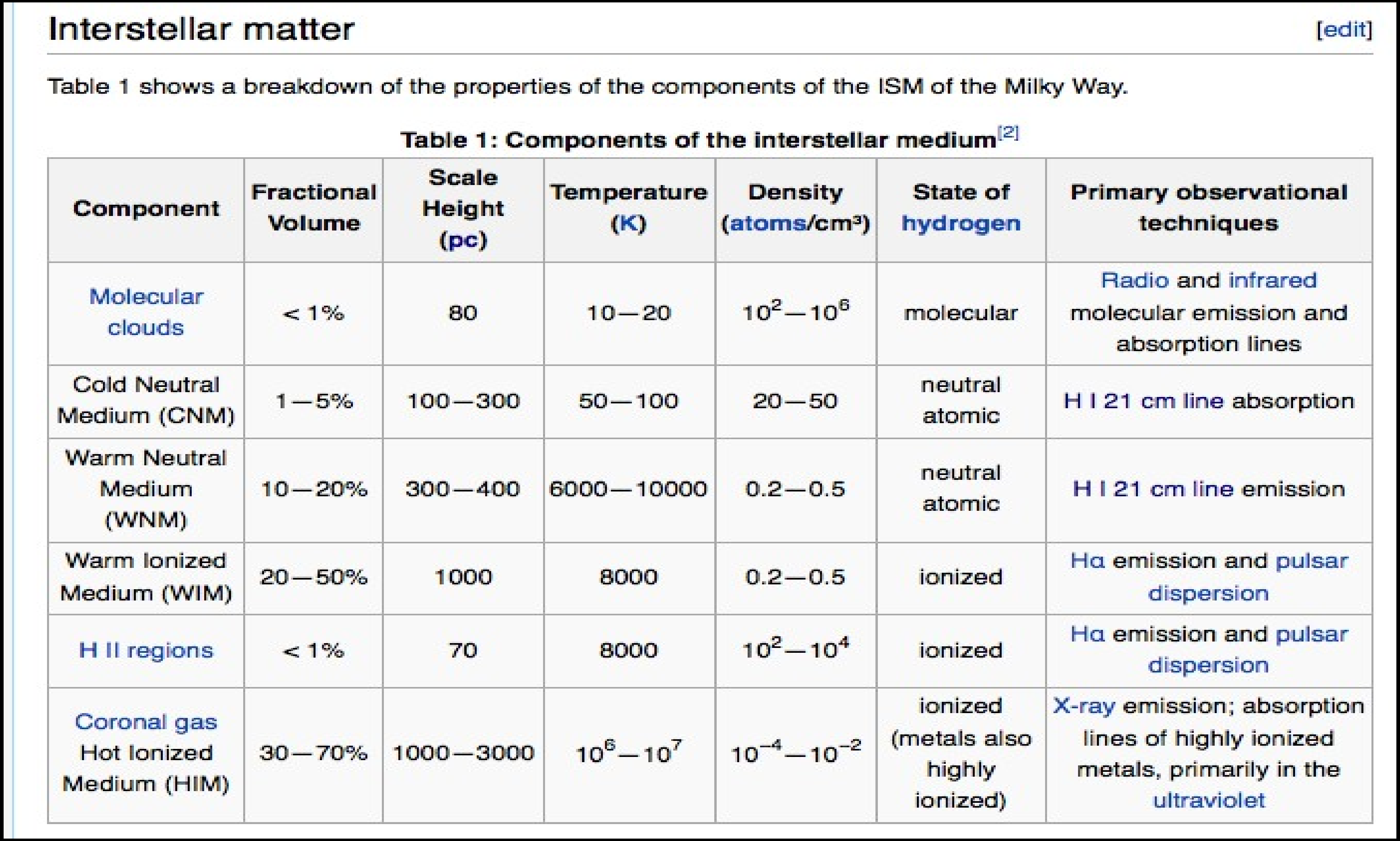


Cold Gas

- Dense molecular clouds
  - $n_H > 10^3$ cm^{-3}
  - $T = 10$ K
  - $f = 0.0001$
- Heating from electrons/cosmic rays.
- Self-gravitating.
- Star formation.
- Observed from CO lines.
- IR dust emission.



Summary



Interstellar matter

[edit]

Table 1 shows a breakdown of the properties of the components of the ISM of the Milky Way.

Table 1: Components of the interstellar medium[2]

Component	Fractional Volume	Scale Height (pc)	Temperature (K)	Density (atoms/cm³)	State of hydrogen	Primary observational techniques
Molecular clouds	< 1%	80	10—20	10^2—10^6	molecular	Radio and infrared molecular emission and absorption lines
Cold Neutral Medium (CNM)	1—5%	100—300	50—100	20—50	neutral atomic	H I 21 cm line absorption
Warm Neutral Medium (WNM)	10—20%	300—400	6000—10000	0.2—0.5	neutral atomic	H I 21 cm line emission
Warm Ionized Medium (WIM)	20—50%	1000	8000	0.2—0.5	ionized	Hα emission and pulsar dispersion
H II regions	< 1%	70	8000	10^2—10^4	ionized	Hα emission and pulsar dispersion
Coronal gas Hot Ionized Medium (HIM)	30—70%	1000—3000	10^6—10^7	10^{-4}—10^{-2}	ionized (metals also highly ionized)	X-ray emission; absorption lines of highly ionized metals, primarily in the ultraviolet

http://en.wikipedia.org/wiki/Interstellar_medium

Abundances

- Start with Big Bang.
- Evolve through stellar nucleosynthesis.
- Back to stars.

Z	X	$\langle m_X \rangle$/amu	$N_X/N_{\rm H}$	$M_X/M_{\rm H}$	Source
1	H	1.0080	1	1	
2	He	4.0026	$9.55 \times 10^{-2\pm0.01}$	3.82×10^{-1}	Photospheric
3	Li	6.941	$2.00 \times 10^{-9\pm0.05}$	1.38×10^{-8}	Meteoritic
4	Be	9.012	$2.19 \times 10^{-11\pm0.03}$	1.97×10^{-10}	Meteoritic
5	B	10.811	$6.76 \times 10^{-10\pm0.04}$	7.31×10^{-9}	Meteoritic
6	C	12.011	$2.95 \times 10^{-4\pm0.05}$	3.54×10^{-3}	Photospheric
7	N	14.007	$7.41 \times 10^{-5\pm0.05}$	1.04×10^{-3}	Photospheric
8	O	15.999	$5.37 \times 10^{-4\pm0.05}$	8.59×10^{-3}	Photospheric
9	F	18.998	$2.88 \times 10^{-8\pm0.06}$	5.48×10^{-7}	Meteoritic
10	Ne	20.180	$9.33 \times 10^{-5\pm0.10}$	1.88×10^{-3}	Photospheric
11	Na	22.990	$2.04 \times 10^{-6\pm0.02}$	4.69×10^{-5}	Meteoritic
12	Mg	24.305	$4.37 \times 10^{-5\pm0.04}$	1.06×10^{-3}	Photospheric
13	Al	26.982	$2.95 \times 10^{-6\pm0.01}$	8.85×10^{-5}	Meteoritic
14	Si	28.086	$3.55 \times 10^{-5\pm0.04}$	9.07×10^{-4}	Photospheric
15	P	30.974	$3.23 \times 10^{-7\pm0.03}$	1.00×10^{-5}	Photospheric
16	S	32.065	$1.45 \times 10^{-5\pm0.03}$	4.63×10^{-4}	Photospheric
17	Cl	35.453	$1.86 \times 10^{-7\pm0.06}$	6.60×10^{-6}	Meteoritic
18	Ar	39.948	$2.75 \times 10^{-6\pm0.13}$	1.10×10^{-4}	Photospheric
19	K	39.098	$1.32 \times 10^{-7\pm0.02}$	5.15×10^{-6}	Meteoritic
20	Ca	40.078	$2.14 \times 10^{-6\pm0.02}$	8.57×10^{-5}	Meteoritic
21	Sc	44.956	$1.23 \times 10^{-9\pm0.02}$	5.53×10^{-8}	Meteoritic
22	Ti	47.867	$8.91 \times 10^{-8\pm0.03}$	4.27×10^{-6}	Meteoritic
23	V	50.942	$1.00 \times 10^{-8\pm0.02}$	5.09×10^{-7}	Meteoritic
24	Cr	51.996	$4.79 \times 10^{-7\pm0.01}$	2.49×10^{-5}	Meteoritic
25	Mn	54.938	$3.31 \times 10^{-7\pm0.01}$	1.82×10^{-5}	Meteoritic
26	Fe	55.845	$3.47 \times 10^{-5\pm0.04}$	1.94×10^{-3}	Photospheric
27	Co	58.933	$8.13 \times 10^{-8\pm0.01}$	4.79×10^{-6}	Meteoritic
28	Ni	58.693	$1.74 \times 10^{-6\pm0.01}$	1.02×10^{-4}	Meteoritic
29	Cu	63.546	$1.95 \times 10^{-8\pm0.04}$	1.24×10^{-6}	Meteoritic
30	Zn	65.38	$4.68 \times 10^{-8\pm0.04}$	3.06×10^{-6}	Meteoritic
31	Ga	69.723	$1.32 \times 10^{-9\pm0.02}$	9.19×10^{-8}	Meteoritic
32	Ge	72.64	$4.17 \times 10^{-9\pm0.04}$	3.03×10^{-7}	Meteoritic

Mass Cycle

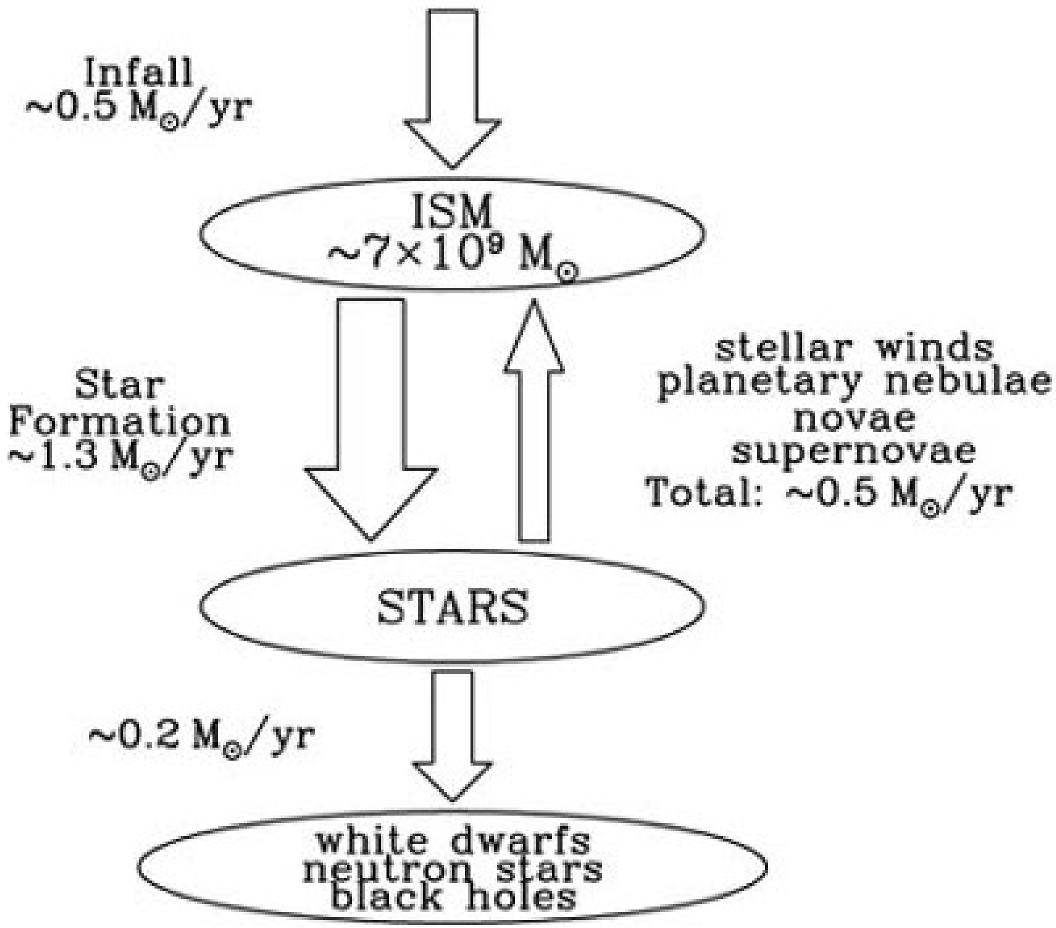


Figure 1.1 Flow of baryons in the Milky Way. See Table 1.2 for the ISM mass budget, and §42.4 for the value of the star formation rate in the Milky Way.

Energy Flow

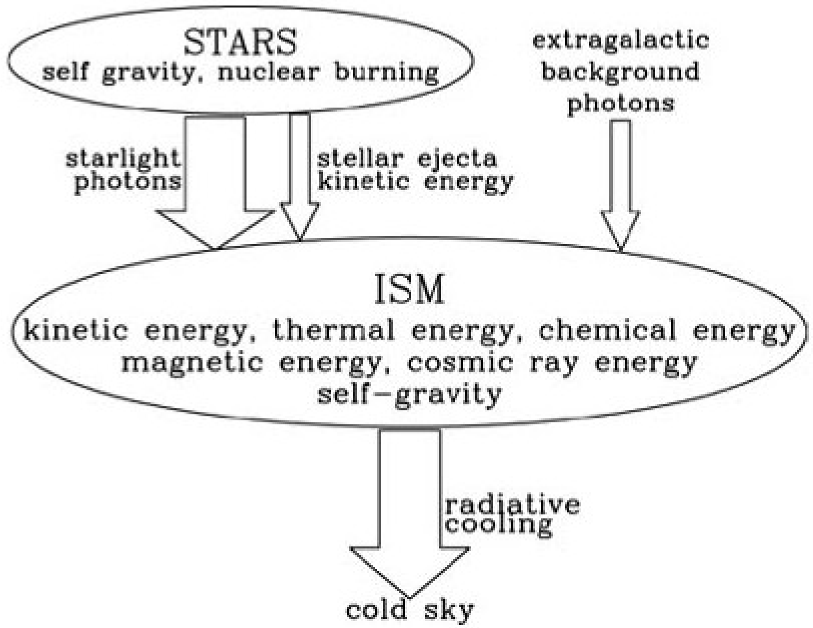


Figure 1.3 Flow of energy in the Milky Way.

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Component	Fractional Volume	Scale Height (pc)	Temperature (K)	Density (atoms/cm³)	State of hydrogen	Primary observational techniques
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Interstellar Radiation

- Galactic synchrotron emission

- From (relativistic) accelerated charged particles.
- Relativistic electrons in the Galactic magnetic field.
- Enhancements near SNR.

Synchrotron Radiation

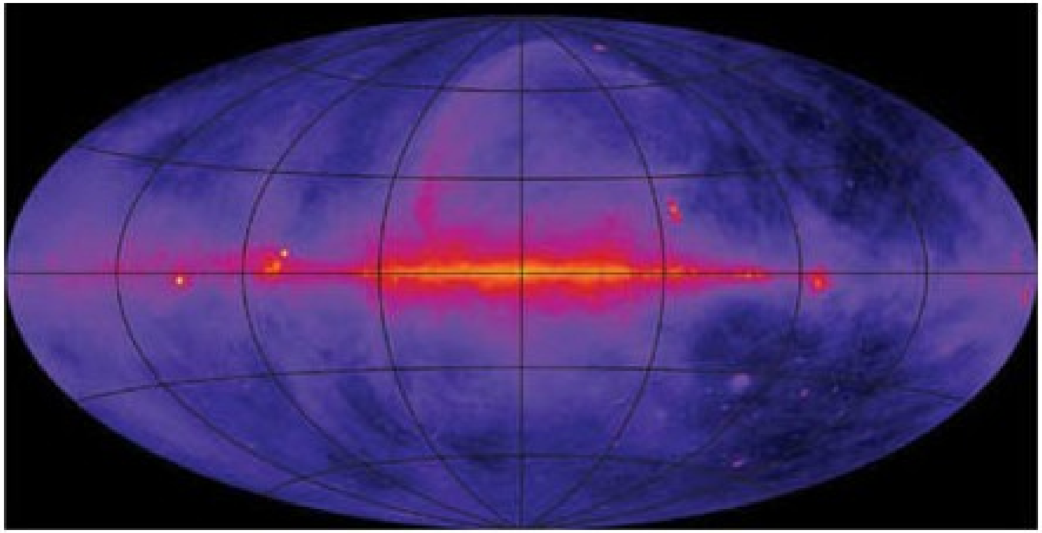


Plate 4. All-sky map of 408 MHz continuum emission (Haslam et al. 1982), synchrotron radiation from highly relativistic electrons. In addition to bright emission along the Galactic plane, there are conspicuous extensions above and below the plane, in particular the so-called North polar spur, starting from the Galactic plane at $\ell \approx 15°$ and extending upward in a loop-like geometry. Bright sources in the Galactic plane include: the Vela/Puppis SNR near (261°, –3°), Sgr A at the Galactic Center; the Cygnus superbubble near (85°, 0), and Cas A at (112°, –2°). The LMC and SMC are visible. Image produced by NASA SkyView, using data from Max-Planck Institüt für Radioastronomie.

Interstellar Radiation

- Galactic synchrotron emission
- Lorentz force:
  - $\mathbf{F} = e[\mathbf{E} + (1/c)(\mathbf{v} \times \mathbf{B})$
- Equations of motion:
  - $d(\gamma m v)/dt = (q/c)\, \mathbf{v} \times \mathbf{B}$.
- F is perpendicular to B so $|\mathbf{v}|$ is a constant.
- Helical motion.
  - $\omega = qB/\gamma mc$

Interstellar Radiation

- Galactic synchrotron emission
- Lorentz force:
  - $\mathbf{F} = e[\mathbf{E} + (1/c)(\mathbf{v} \times \mathbf{B})$
- $d(\gamma m v)/dt = (q/c)\, \mathbf{v} \times \mathbf{B}$.
- $P = 4/3\ \sigma_T\ c\beta^2\gamma^2 U_B$
  - $\sigma_T = 8\pi r_0^2/3$
  - $U_B = B^2/8\pi$
  - β is the speed

Interstellar Radiation

- Galactic synchrotron emission

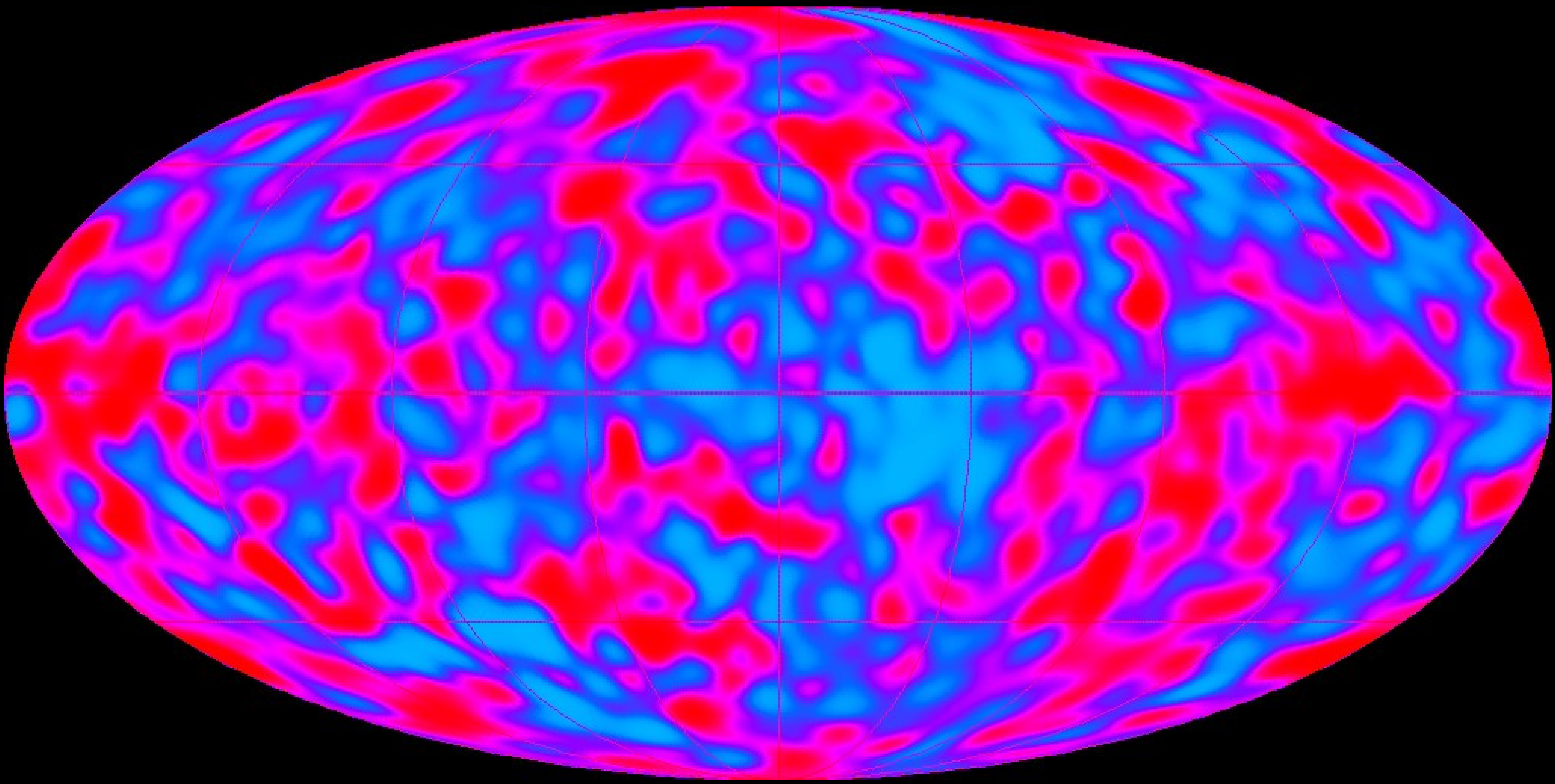
- Radiation beamed about velocity vector.
- $P(\nu) \propto \nu^{-s}$
  - $s = (p - 1)/2$
  - particle energy: p
- Observations:
  - 0.4 – 23 GHz
  - $\nu u_{\nu} = 3 \cdot 10^{-19} \nu^{0.1}$ erg cm^{-3}
- Radiation polarized.

Interstellar Radiation

- Galactic synchrotron emission
- Cosmic microwave background

- Blackbody radiation.
  - T = 2.755 K
- Isotropic, homgenous.
  - Some peculiar motion due to Sun, Virgo etc.

CMBR



Interstellar Radiation

- Galactic synchrotron emission
- Cosmic microwave background
- Free-free emission.
- Bremsstahlung.
  - Electron is inelastically scattered with emission of a photon.
  - Continuum emission.

Interstellar Radiation

- Galactic synchrotron emission
- Cosmic microwave background
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  - Electron is inelastically scattered with emission of a photon.
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$$j_{\mathrm{ff},\nu} = \frac{8}{3}\left(\frac{2\pi}{3}\right)^{1/2} g_{\mathrm{ff},i}\,\frac{e^6}{m_e^2 c^3}\left(\frac{m_e}{kT}\right)^{1/2} \mathrm{e}^{-h\nu/kT} n_e Z_i^2 n_i$$

$$= 5.444 \times 10^{-41} g_{\mathrm{ff}} T_4^{-1/2} \mathrm{e}^{-h\nu/kT} Z_i^2 n_i n_e \,\mathrm{erg\,cm^3\,s^{-1}\,sr^{-1}\,Hz^{-1}},$$

  - where *j* is the free-free emissivity (power per unit frequency per unit volume per steradian)

Interstellar Radiation

- Galactic synchrotron emission
- Cosmic microwave background
- Free-free emission.

$$\Lambda_{\mathrm{ff}} = 4\pi \int_0^\infty j_{\mathrm{ff},\nu}\, d\nu = \frac{32\pi}{3} \left(\frac{2\pi}{3}\right)^{1/2} \frac{e^6}{m_e^2 h c^3} \left(m_e k T\right)^{1/2} \langle g_{\mathrm{ff}} \rangle_T Z_i^2 n_i n_e$$

- Radiated power $\propto n_i n_e T^{1/2}$

Interstellar Radiation

- Galactic synchrotron emission
- Cosmic microwave background
- Free-free emission.
  - Absorption.

$$j_{\mathrm{ff},\nu} = \frac{8}{3}\left(\frac{2\pi}{3}\right)^{1/2} g_{\mathrm{ff},i}\,\frac{e^6}{m_e^2 c^3}\left(\frac{m_e}{kT}\right)^{1/2} \mathrm{e}^{-h\nu/kT} n_e Z_i^2 n_i$$
$$= 5.444\times 10^{-41} g_{\mathrm{ff}} T_4^{-1/2} \mathrm{e}^{-h\nu/kT} Z_i^2 n_i n_e \,\mathrm{erg\,cm^3\,s^{-1}\,sr^{-1}\,Hz^{-1}},$$

- Using Kirchoff's Law.

$$\kappa_{\mathrm{ff},\nu} = \frac{4}{3}\left(\frac{2\pi}{3}\right)^{1/2} \frac{e^6}{m_e^{3/2}(kT)^{1/2} h c \nu^3}\left[1-\mathrm{e}^{-h\nu/kT}\right] Z_i^2 n_i n_e g_{\mathrm{ff}}$$

- if hν << kT

$$\frac{\kappa_{\mathrm{ff},\nu}}{n_i n_e} \approx \frac{4}{3}\left(\frac{2\pi}{3}\right)^{1/2} \frac{e^6}{(m_e kT)^{3/2} c \nu^2} Z_i^2 g_{\mathrm{ff}} \quad (h\nu \ll kT)$$

Interstellar Radiation

- Galactic synchrotron emission
- Cosmic microwave background
- Free-free emission.
- Recombination radiation
- Proportional to $n_e n_i$.
- Radio lines are Rydberg lines.
- Two photon emission.

Interstellar Radiation

- Galactic synchrotron emission
- Cosmic microwave background
- Free-free emission.
- Recombination radiation
- Starlight
- Integrated light of all stars.
- UV sky dominated by B stars.
- Visible sky by cool stars.
- Normally people use MMP model.

Interstellar Radiation

- Galactic synchrotron emission.
- Cosmic microwave background.
- Free-free emission.
- Recombination radiation
- Starlight.
- Dust emission.
- Scattered light from interstellar dust.
- Thermal emission from dust.
    - Stochastic emission from small grains.

Summary

Table 12.1 Interstellar Radiation Field (ISRF) Components

Component		$u_{\rm rad}$ ($\mathrm{erg\,cm^{-3}}$)
Radio synchrotron [Eq. (12.2)]		2.7×10^{-18}
CMB, $T = 2.725\,\mathrm{K}$		4.19×10^{-13}
Dust emission		5.0×10^{-13}
Free–free, free–bound, two-photon		4.5×10^{-15}
Starlight: $T_1 = 3000\,\mathrm{K}$, $W_1 = 7 \times 10^{-13}$	4.29×10^{-13}	
$T_2 = 4000\,\mathrm{K}$, $W_2 = 1.65 \times 10^{-13}$	3.19×10^{-13}	
$T_3 = 7500\,\mathrm{K}$, $W_3 = 1 \times 10^{-14}$	2.29×10^{-13}	
$\lambda < 2460\,\mathrm{Å}$ UV (Eq. 12.7)	7.11×10^{-14}	
Starlight total		1.05×10^{-12}
Hα		8×10^{-16}
Other $\lambda \geq 3648\,\mathrm{Å}$ H lines = $1.1 \times$ Hα:		9×10^{-16}
$0.1 - 2\,\mathrm{keV}$ x rays		1×10^{-17}
ISRF total		2.19×10^{-12}