

I. Introduction

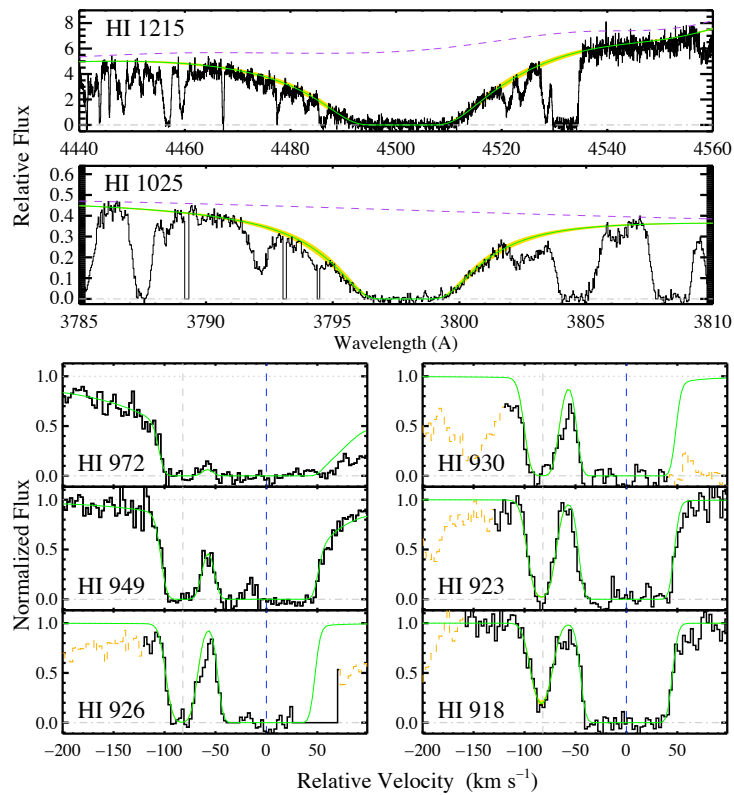
A. Baryon Budget

- Most of the baryons in the universe are in low density gas
- Baryonic mass density: Ω_b

$$\Omega_b \equiv \frac{\rho_b}{\rho_c} = 0.04 h_{75}^{-2} \quad (1)$$

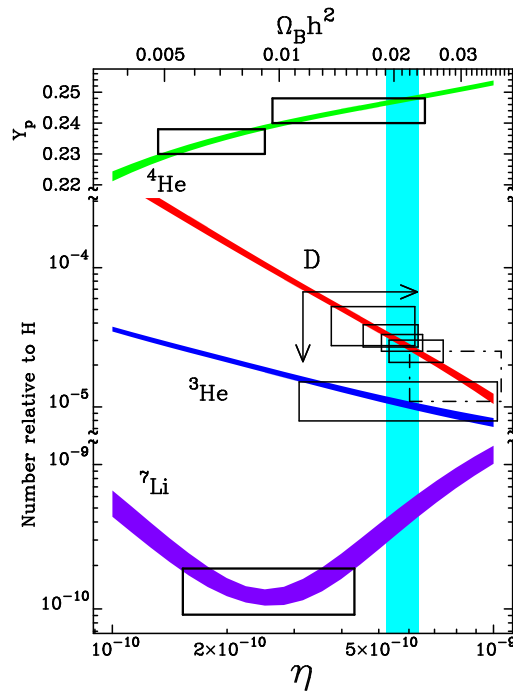
◇ ρ_c is the critical density

$$\rho_c \equiv \frac{3H_0^2}{8\pi G} = 1.05 \times 10^{-29} h_{75}^2 \text{ (cgs)} \quad (2)$$

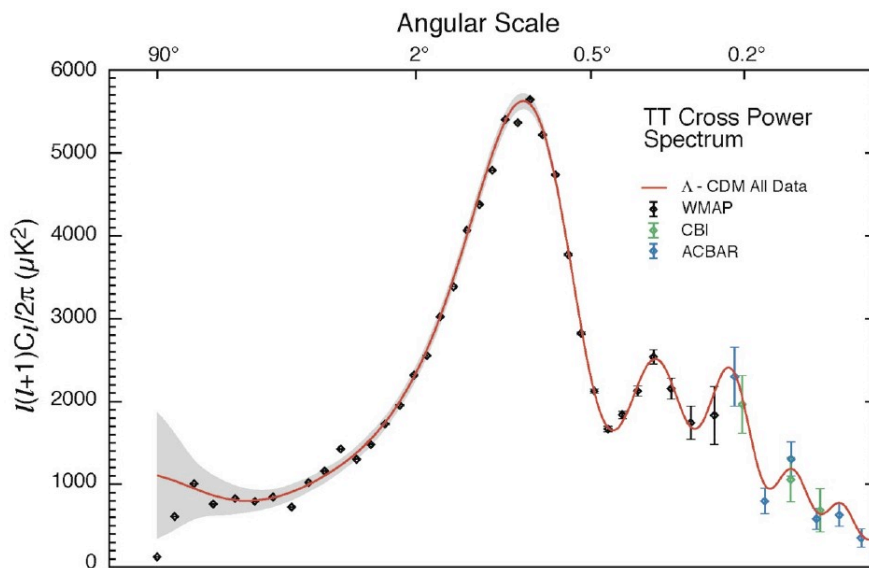


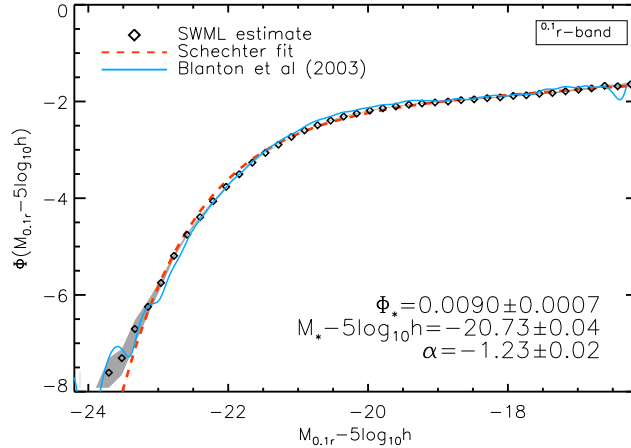
◇ BBN + D/H measurements

- ▲ Quasar absorption line studies (Burles & Tytler 1997)
- ▲ Excellent example of low density astrophysics



- ◇ CMB oscillations
 - ▲ Relative amplitude of 1st and 2nd peaks
 - ▲ WMAP
- ◇ $\Omega_b^{BBN} = \Omega_b^{CMB}$!!!





- Stellar Mass Density: Ω_*

- ◇ Luminosity functions

$$\Phi(M) = (0.4 \ln 10) \phi_* 10^{0.4(M_* - M)(1 + \alpha)} \exp \left[-10^{0.4(M_* - M)} \right] \quad (3)$$

$$\Phi(L) = \phi_* \left(\frac{L}{L_*} \right)^\alpha \exp \left(\frac{-L}{L_*} \right) \quad (4)$$

- ▲ 2DF: Cole et al. 2001, MNRAS, 326, 255

- ▲ SDSS z -band: Blanton et al. 2003, ApJ, 592, 819

- $\phi_* = 1.35 \pm 0.04$ ($\times 10^{-2} h^3 \text{Mpc}^{-3}$)

- $M_* - 5 \log h = -21.18 \pm 0.02$

- $\alpha = -1.08 \pm 0.02$

- ◇ Integrating

$$\Omega_* = \int \phi(L) (M/L) dL \quad (5)$$

- ▲ Mass-to-light ratio: M/L

- ▲ Luminosity weighted: $(M/L_z) = 1.5 \pm 30\%$ (Kauffmann et al. 2003, MNRAS, 341, 33)

$$\Omega_* = 0.0025 \pm 0.0008 \quad (\text{Fukugita 2004, IAU}) \quad (6)$$

- ◇ $\Omega_*/\Omega_b = 0.06$

- ▲ Stars are a small fraction of the baryons

- ▲ Overwhelming majority of baryons are in lower density gas

- Molecular Gas (not quite low density)

- ◇ Discrete ‘clouds’

- ◇ Molecular Hydrogen

- ▲ No permanent dipole moment

- ▲ Rotational transitions are not allowed

- ▲ Furthermore, excitation energy is 87 K (the gas is too cold)
- ▲ H₂ shows primarily UV electronic transitions →
These require absorption-line techniques
- ◇ CO
 - ▲ Imperfect surrogate for H₂
 - ▲ Rotational constant $B = 2.77$ K
 - ▲ Radio observations are possible
- ◇ CO survey (Keres, Yun, & Young 2003, ApJ, 582, 659; Zwaan & Prochaska 2007, ApJ, 643, 675)

$$\Omega_{H_2} = 0.0029 \pm 0.0009 \Omega_b \quad (7)$$

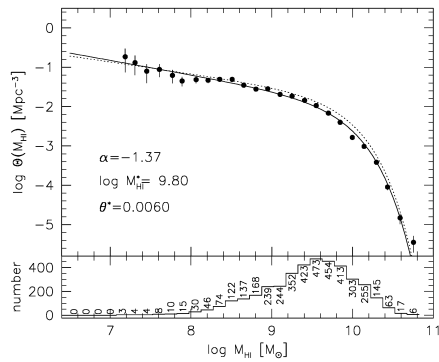


Figure 1. Top: H I mass function from HICAT. The solid line is a Schechter fit to the points; the best-fitting parameters are shown in the lower left corner. Bottom: distribution of H I masses used for the HIMF calculation.

- Atomic Gas (HI)

- ◇ 21cm ‘blind’ surveys
- ◇ HIPASS (Zwaan et al. 2005, MNRAS, 359, L30)

$$\theta(M_{HI})dM_{HI} = \theta^* \left(\frac{M_{HI}}{M_{HI}^*} \right)^\alpha \exp\left(-\frac{M_{HI}}{M_{HI}^*} \right) dM_{HI} \quad (8)$$

- ▲ $\alpha = -1.37 \pm 0.03 \pm 0.05$
- ▲ $\log M_{HI}^* = 9.80 \pm 0.03 \pm 0.03 h_{75}^{-2} M_\odot$
- ▲ $\theta^* = (8.6 \pm 0.8 \pm 0.6) \times 10^{-3} h_{75}^3 \text{ Mpc}^{-3}$
- ◇ Impose He correction (i.e. scale by $\mu = 1.3$)

$$\Omega_{HI} = (3.5 \pm 0.4 \pm 0.4) \times 10^{-4} h_{75}^{-1} \quad (9)$$

- ▲ $\Omega_{HI} = 0.01 \Omega_b$
- ▲ $\sim 80\%$ of the gas is in galaxies like the Milky Way
- ▲ Remainder is in LSB and dwarf galaxies

- Intracluster medium (ICM)

- ◇ X-ray emission
- ◇ $L \propto n_e^2 T$

- ▲ Obtain T from X-ray spectra ($T \approx 10^8$ K)
- ▲ Assume $n_e = n_p$, i.e. fully ionized
- ▲ Impose (or resolve) a radial distribution
- ▲ Analysis gives ratio of hot gas to total mass (Allen et al. 2008, MNRAS, 383, 879)

$$f_{gas} = \frac{M_{HII}}{M_{grav}} = 0.11 \pm 0.01 \quad (10)$$

- ◇ All-sky X-ray survey + SDSS
 - ▲ Gives cluster mass function (Rines et al. 2008, in press)

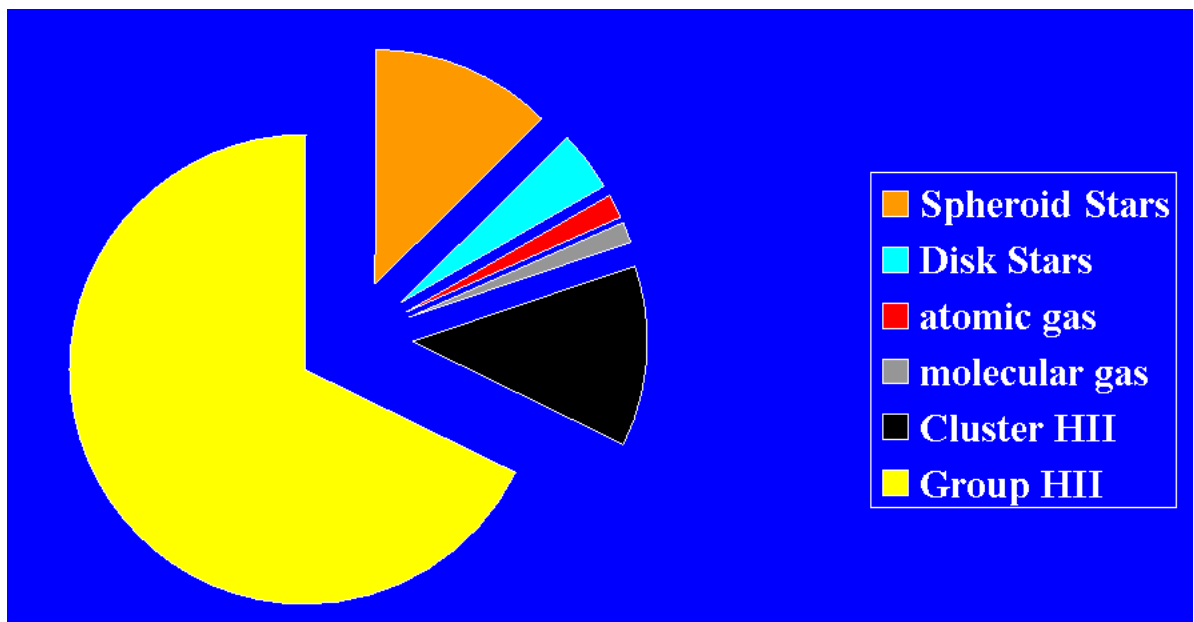
$$\Omega_{cl} = 0.010 \quad (11)$$

- ◇ Hot gas in clusters

$$\Omega_{ICM} = 0.027\Omega_b \quad (12)$$

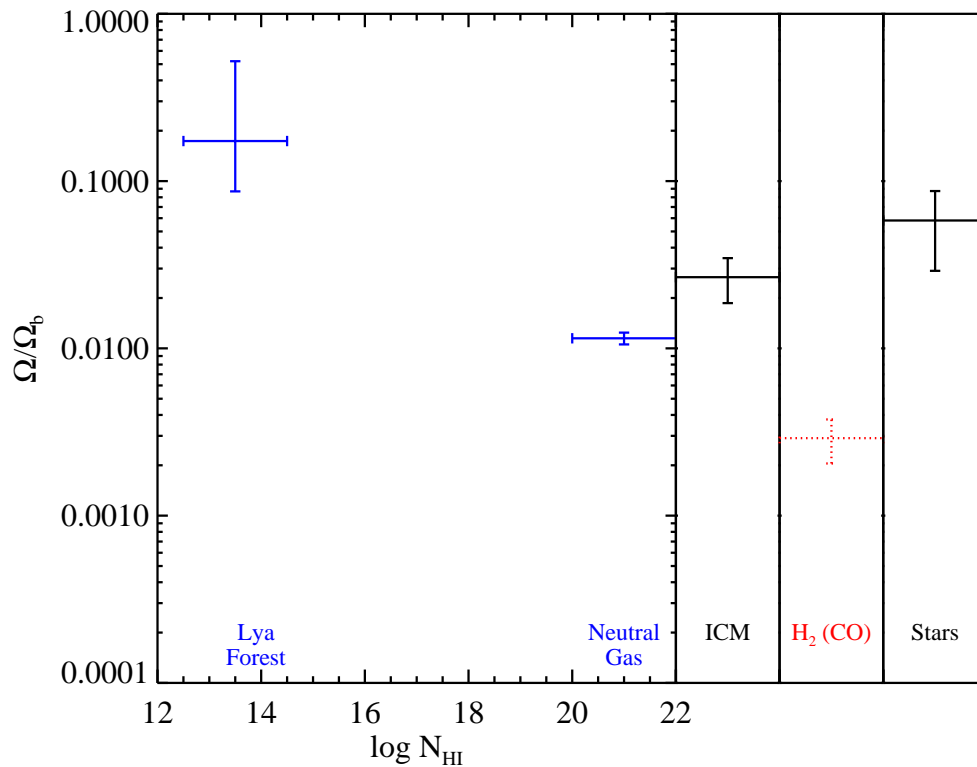
- Subtotal:

$$\Omega_* + \Omega_{H_2} + \Omega_{HI} + \Omega_{clgas} = 0.10\Omega_b \quad (13)$$



- Intergalactic Medium (IGM)
 - ◇ a.k.a. the Ly α Forest
 - ◇ > 90% of the baryons at $z = 3$ (Rauch 1998)
 - ◇ Technique
 - (a) Observe Ly α and measure N_{HI}
 - (b) Adopt ionizing background radiation field (Haardt & Madau 1996)
 - (c) Infer ionization corrections and $\Omega_{Ly\alpha}$
 - ◇ $\Omega_{Ly\alpha}$ at $z = 0$
 - ▲ Under debate

- Radiation field is uncertain
- Extrapolation to low N_{HI} is uncertain
- ▲ 10 to 70% of Ω_b (Prochaska & Tumlinson 2008, in press)



- Warm-Hot Intergalactic Medium (WHIM)
 - ◇ Theoretically motivated
 - ▲ See above
 - ▲ Developed in numerical simulations (Cen & Ostriker 1999; Davé et al. 2001)
 - ◇ Easy to hide low density, warm, ionized gas
 - ◇ Best tracer
 - ▲ OVII, OVIII
 - ▲ **But**, these require X-ray spectroscopy which is very tough
 - ◇ 2nd best signature
 - ▲ OVI (Tripp et al. 2001)
 - ▲ Low T tail of the WHIM
 - ◇ Current estimate

$$\Omega_{\text{OVI}} > 0.1 \Omega_b \quad (14)$$

- Summary

B. ISM Basics (Milky Way)

Table 1: Empirical Summary of Baryons in the Universe

Phase	Temperature (K)	$\Omega(z = 3)$		$\Omega(z = 0)$	
		Location	Estimate ^a	Location	Estimate ^a
Stars	–	Galaxies	0.005 ± 0.002	Galaxies	0.06 ± 0.03
Molecular Gas	10^2	Galaxies	> 0.001	Galaxies	0.0029 ± 0.0015
Neutral Gas	10^3	Galaxies	0.016 ± 0.002	Galaxies	0.011 ± 0.001
Ionized Gas	10^4	IGM	> 0.80	IGM	$0.17^{+0.2}_{-0.05}$
Warm/Hot Gas	10^6	Galaxies?	> 0.01	Filaments?	??
Hot Gas	10^7	??	??	Clusters	0.027 ± 0.009

^a Relative to an assumed Ω_b value of 0.043.

- Overall

- ◊ $M_{gas} = 5 \times 10^9 M_\odot$ (vs. $M_{star} = 10^{11} M_\odot$)
- ◊ The ISM is very inhomogeneous :: Multi-phase
- ◊ Supernovae explosions, cosmic rays, dust, and magnetic fields are all major players

Table 2: ISM SUMMARY

Phase	T (K)	$\langle n_H \rangle$ (cm^{-3})	nT (K cm^{-3})	f_V	f_M	Observe
H ₂	5–30	$10^2 - 10^5$	$\gtrsim 10^3$	0.005	0.5	CO, UV absorp
HI (CNM)	20–100	5–20	$\sim 10^3$	0.05	0.4	21cm, UV
HI (WNM)	8000	0.5	$\sim 10^3$	0.40		21cm, UV
HVC	??	??	??	> 0.2	??	21cm, UV, H α
WIM	8000	0.3	2.4×10^3	0.5	0.1	H α
HII Regions	10^4	$10 - 10^4$	$10^5 - 10^8$	0.001	0.02	H α
HIM	5×10^5	0.005	2.5×10^3	0.5	0.001	OVI, X-rays
dust	5 – 50				0.01	IR, UV inference
CR	$E > 10 \text{ MeV}$			1		Direct

- H₂ gas

- ◊ Majority is in dense, massive ‘clouds’
 - ▲ $n(M) \propto M^{-1.6}$
 - ▲ Most massive molecular clouds have $M \sim 10^6 M_\odot$
- ◊ Observations (Radio emission)
 - ▲ H₂ is difficult because it has no permanent dipole
 - ▲ CO acts as a molecular tracer
 - ¹²CO – thick :: Temperature, kinematic diagnostic
 - ¹³CO – thin :: Density diagnostic
- ◊ Observations (UV absorption)

- ▲ UV transitions – Werner bands
- ▲ Very complicated level populations
- ▲ Potentially useful T , density diagnostics

- HI gas

- ◊ Observations

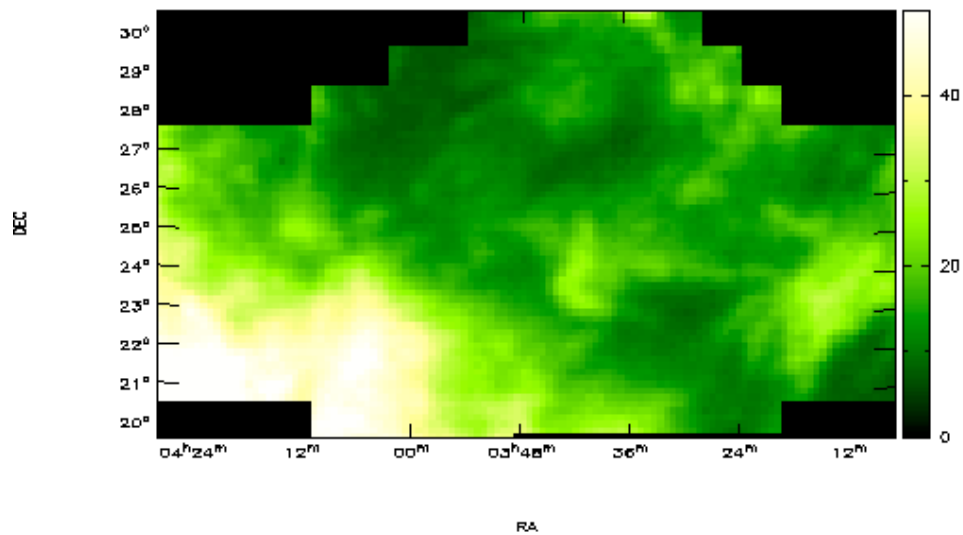
- ▲ 21cm absorption

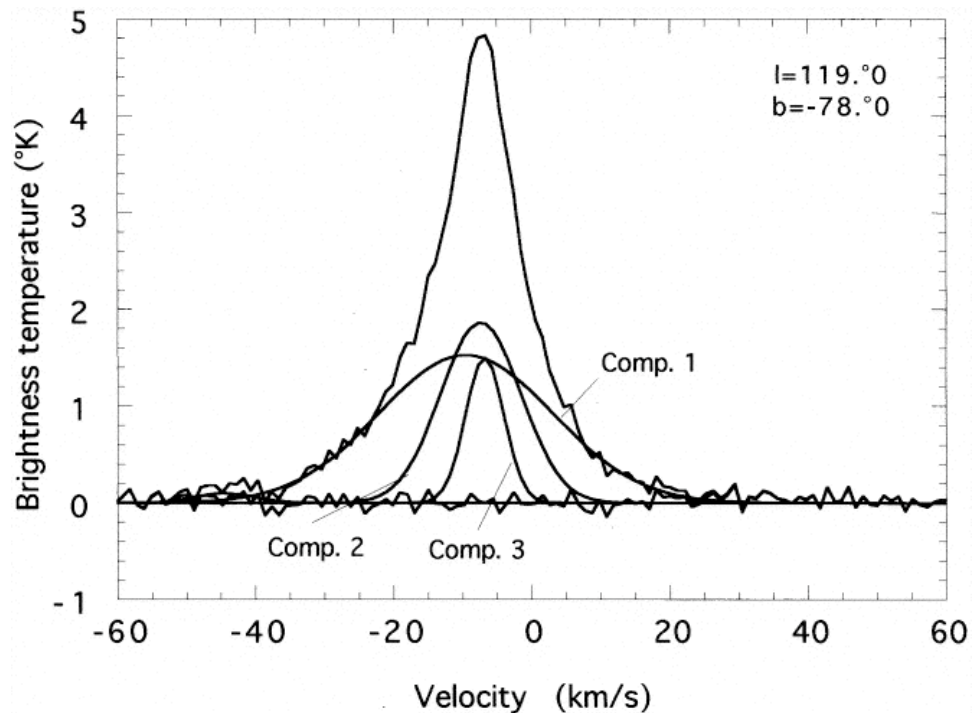
$$\tau_{21} = \frac{N_{\text{HI}}}{1.825 \times 10^{18}} \frac{\phi(v)}{T_s} \quad (15)$$

- ISM is optically thin ($\tau \lesssim 1$) on most sightlines
- Differential rotation helps limit τ_{21}

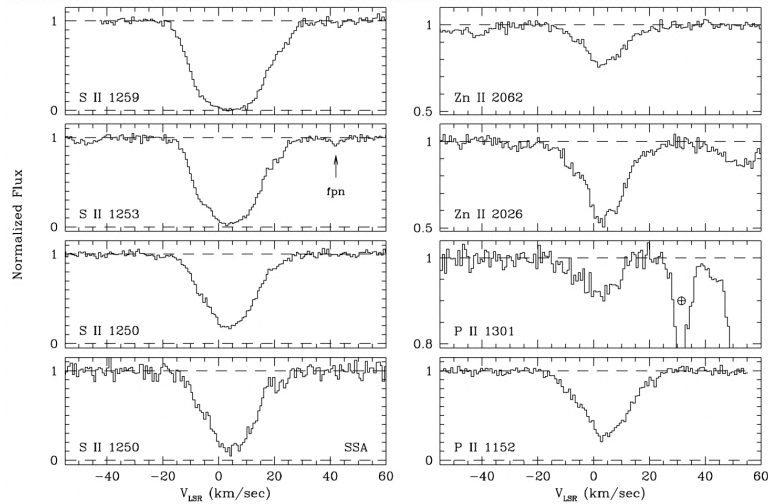
- ▲ 21cm emission :: Brightness temperature

- Line profiles reveal neutral gas at two temperatures

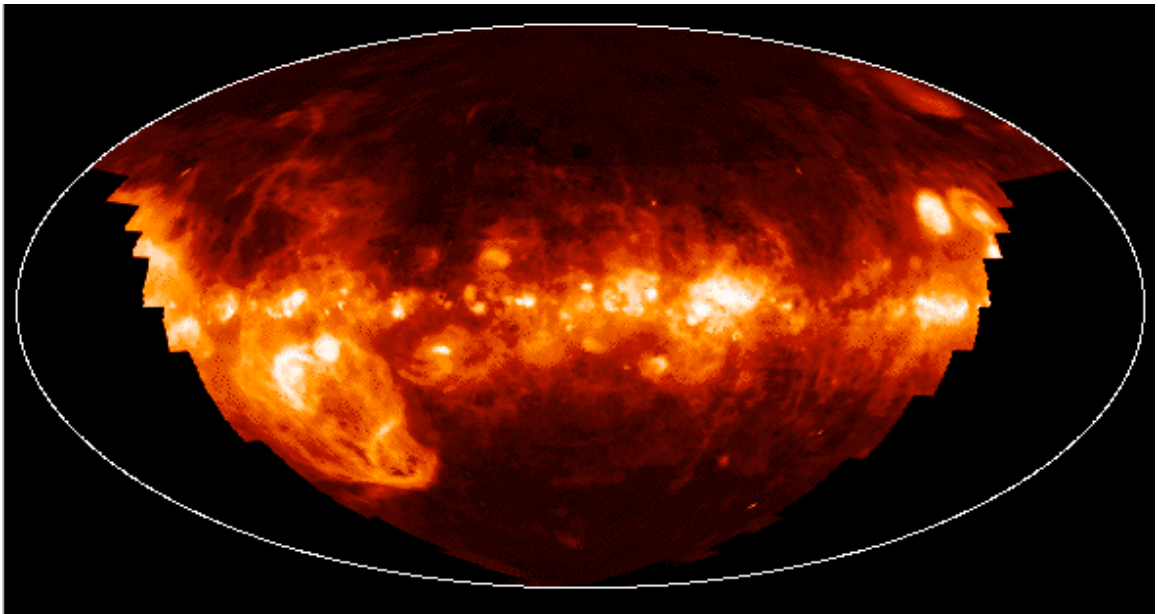




- ◇ Cold Neutral Medium (CNM)
 - ▲ $T \sim 100$ K
 - ▲ $n \sim 10 \text{ cm}^{-3}$
 - ▲ Likely precursor to molecular clouds
 - ▲ Confined to few 100pc from midplane
 - ▲ Identified in 21cm emission and absorption (+UV, Optical)
- ◇ Warm Neutral Medium (WNM)
 - ▲ Fills far more of the ISM than the CNM
 - ▲ $T \sim 8000$ K
 - ▲ $n \sim 0.1 \text{ cm}^{-3}$
 - ▲ The “Local bubble” is likely a WNM
 - ▲ Identified primarily in 21cm emission
- ◇ CNM and WNM are believed to be in pressure equilibrium
 - ▲ The “classic” two-phase ISM (Field, Goldsmith, & Habing 1969)
 - ▲ **But**, this classical picture is incomplete

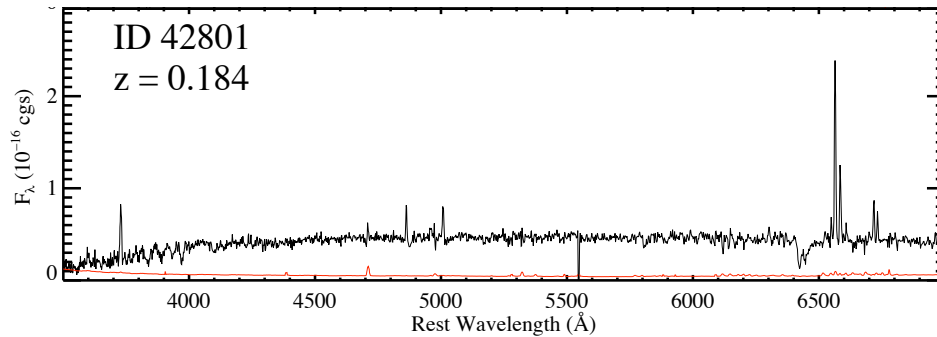


- ◇ UV and Optical metal absorption
 - ▲ UV – FeII, ZnII, SII:: Abundances and dust depletion
 - ▲ Optical – NaI, CaII:: Not the dominant ions of these elements. Reveals gas kinematics and traces the CNM



- Warm Ionized Medium (WIM)
 - ◇ Extensive H α emission throughout the Milky Way
 - ◇ Reynolds Layer
 - ▲ Extends one to many kpc above the midplane
 - ▲ Active area of research (<http://www.astro.wisc.edu/wham>)
 - ◇ Origin
 - ▲ Supernovae feedback
 - ▲ SN blows ‘chimneys’ in neutral ISM
 - ▲ O and B stars ionize, heat the gas via the chimneys

- HII Regions
 - ◊ Bounded WIM (ionization bounded)
 - ▲ Ionized by O and B stars
 - ▲ Observed in $H\alpha$, [OIII], etc.
 - ◊ Origin of galaxy emission lines



- Hot ionized medium (HIM)
 - ◊ Observations
 - ▲ OVI, CIV gas in collisional equilibrium
 - ▲ Soft X-ray observations
 - ▲ The HIM (both locally and throughout the Galaxy) limits X-ray research at energies < 1 keV
 - ◊ Origin
 - ▲ SN shocks
 - ▲ Galactic fountain
- Dust
 - ◊ Major player in all of astrophysics
 - ◊ Solid phase component
 - ◊ Observations
 - ▲ Reddening of stars in Galactic plane
 - ▲ Differential depletion of refractory elements
 - ▲ IR emission
 - ◊ Predominantly located (by mass) in the CNM and H_2 clouds but found in all phases
 - ◊ Critical probe of starburst and massive galaxies
 - ▲ Optical and UV light reemitted in IR
 - ▲ Also critical for obscured AGN
- Cosmic Rays
 - ◊ Ions accelerated by SN shocks
 - ◊ Scattered throughout the Galaxy
 - ◊ Critical ionizing mechanism

▲ Catalyst for the multi-phase ISM

- Photons
 - ◇ Predominant heating source (via dust grains)
 - ◇ Maintains portions of the WIM
- ISM Energy densities
 - ◇ Thermal energy

$$u_{therm} = \frac{3}{2}P = 0.9 \left(\frac{P/k}{3000 \text{ cm}^3\text{K}} \right) \text{ eV cm}^{-3} \quad (16)$$

- ◇ Hydrodynamic energy

$$u_{hydro} = \frac{1}{2}\rho \langle v^2 \rangle = 0.18 \left(\frac{n_H}{\text{cm}^{-3}} \right) \left(\frac{v_{rms}}{5\text{km/s}} \right)^2 \text{ eV cm}^{-3} \quad (17)$$

- ◇ Magnetic energy

$$u_{magnetic} = \frac{B^2}{8\pi} = 0.22 \left(\frac{B}{3\mu\text{G}} \right)^2 \text{ eV cm}^{-3} \quad (18)$$

- ◇ Starlight

$$u_{starlight} = 0.5 \text{ eV cm}^{-3} \quad (19)$$

- ◇ Cosmic rays

$$u_{CR} = 0.8 \text{ eV cm}^{-3} \quad (20)$$

- ◇ CMB

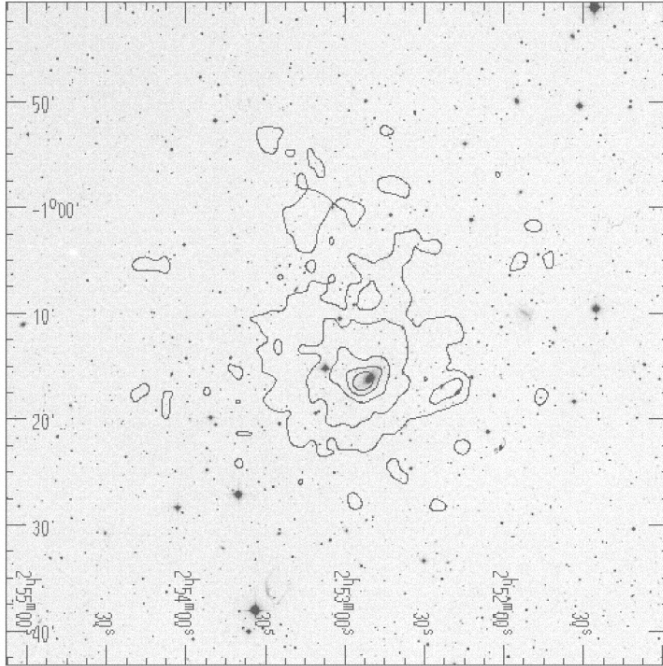
$$u_{CMB} = 0.25 \text{ eV cm}^{-3} \quad (21)$$

- ◇ Conspiracy?! (Burbidge 1967)
- ◇ First few of these quantities are probably coupled by MHD turbulence

C. ISM in E (and S0) Galaxies

- General expectation :: These galaxies have no gas
 - ◇ Rarely observe dust lanes
 - ◇ 21cm emission is negligible
- $T \sim T_{vir} \sim 10^7 \text{ K}$
- Example: NGC 4472 in Virgo
 - ◇ $M_{tot} = 4 \times 10^{13} M_{\odot}$
 - ◇ $M_* = 7 \times 10^{11} M_{\odot}$
 - ◇ $M_{hotgas} = 10^{11} M_{\odot}$
 - ◇ $M_{hotgas}/M_* \approx 1/7$; similar to spiral galaxies
- ISM replaced by

- (a) Mass loss from evolving stars
 - ◇ Stellar winds
 - ◇ Planetary nebulae
- (b) Infall from IGM



- Cooling conundrum (consider NGC 4472; fig shows NGC 1132 from Mulchaey & Zabludoff 1999, ApJ, 514, 133)
 - ◇ $L_x = 4.5 \times 10^{41}$ erg/s for 0.5–4.5 keV
 $\Rightarrow L_x \approx 7 \times 10^{41}$ erg/s (Bolometric)
 - ◇ 10^7 K gas emits X-rays at 1 keV
 - ◇ Cooling rate

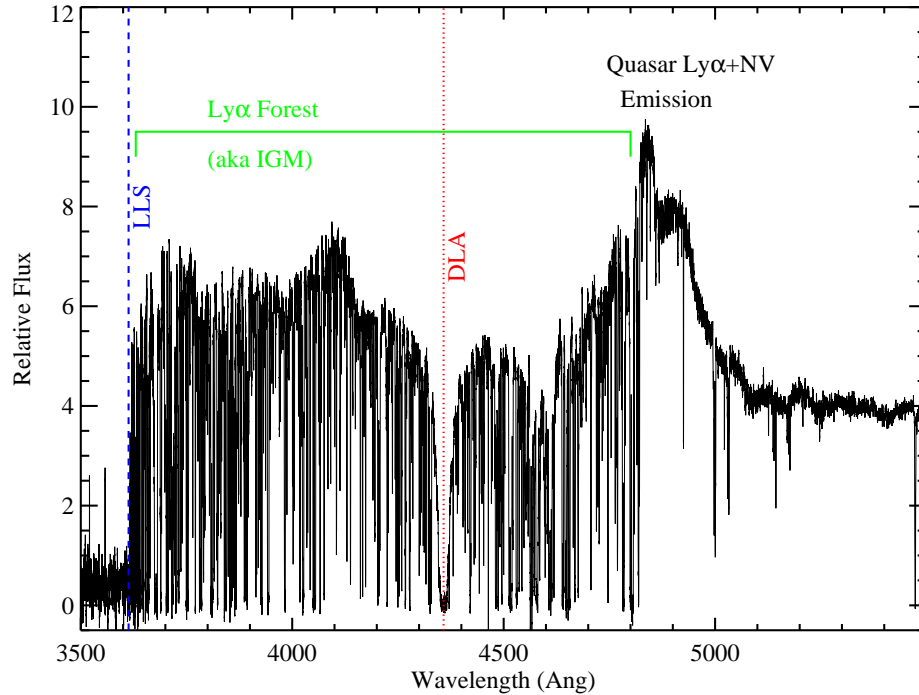
$$\dot{M} = \frac{L_x}{(kT/\mu m_p)} \quad (22)$$

$$\approx 2 - 3 M_\odot/\text{yr} \quad (23)$$

- ◇ Hot cooling gas with $T \sim 10^6$ K is not observed. Why?!

D. IGM Basics

- Observations
 - ◇ High redshift quasar spectra
 - ◇ Predominance of narrow absorption features
- Ly α :: Dominant feature



- Ly α Forest
 - ◊ $N_{\text{HI}} < 10^{17} \text{ cm}^{-2}$
 - ◊ Traces the lowest density gas :: $\delta \equiv \delta\rho/\rho < 10$
 - ◊ Filaments of the cosmic web
 - ◊ Predominantly photoionized
 - ▲ $T \sim 10^4 \text{ K}$
 - ▲ Metal enriched
- Lyman limit systems
 - ◊ $\tau_{\text{Ly}\alpha} > 1$
 - ◊ $N_{\text{HI}} > 10^{17} \text{ cm}^{-2}$
 - ◊ Galaxies, large-scale structure?
- Damped Ly α Systems
 - ◊ $N_{\text{HI}} > 2 \times 10^{20} \text{ cm}^{-2}$
 - ◊ Galactic disks today
 - ◊ ISM of young galaxies at high z

E. ICM

- Collisionally ionized gas ($T > 10^7 \text{ K}$)
- Bremsstrahlung radiation :: X-rays
 - ◊ X-ray spectra define the temperature T

- ◇ X-ray luminosity constrains $n_e^2 T$, which gives a mass estimate
- SZ effect