PROBING REIONIZATION WITH CMB POLARIZATION

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Summary :

① MAP can detect the reionization feature in CMB polarization.

② $\sigma(\tau) \simeq 0.05$ (MAP)

③ More info in CMB polarization spectra then just τ.

④ Planck (and MAP if τ is high) can differentiate between 2 models with the same τ but different reionization histories.

⑤ Large angle CMB polarization is vital if we are to pin down the amplitude of primordial fluctuations.

astro-ph/0207591
ApJ 2002

What does it take to reionize the universe ?

$$E_{nuc} \sim f_* \frac{28.3\,\mathrm{MeV}}{4} n_B = 7 n_B f_* \,\mathrm{MeV}$$

$$E_{ion} \sim 7 n_B f_* f_{>13.6\,\mathrm{eV}} \,\mathrm{MeV}$$

$$\frac{E_{ion}}{\bar{e}_{ion}} \simeq n_H \Longrightarrow f_* \sim \frac{10^{-6}}{f_{>13.6\,\mathrm{eV}}}$$

(One ionizing photon for every H atom)

$100\,M_\odot \longrightarrow 10^5\,\mathrm{K}$ Blackbody spectrum

However :

Recombinations happen.

$$\frac{R}{H} \simeq \left(\frac{1+z}{11}\right)^{1.5}$$

Ionizing photon production rate must offset this.

(For more info. see Barkana & Loeb
astro-ph/0010468)

Ionizing Sources

Stars, Quasars, . . .

Requirements:

① Ionize all H. ② Keep it ionized.

Ionizing photon production rate depends on:

- Rate at which gas is converted into new ionizing sources.
- IMF of the ionizing source population
- γ production rate per source.
- Fraction of photons escaping into the IGM.
- Clumping factor.

Important inputs: η_{phot}, f_{esc}, C, f_{coll}

$n_{phot} = 10^4$ (Venkatesan, Tumlinson, Shull astroph/0206390)

$f_{esc} = 1$

$C = 20$

$f_{coll}\,(T_{vir} > 10^4 K)$: Press-Schechter

$\Longrightarrow z_{max} = 21 \quad (\tau_{max} = 0.18)$

(for more info on semi-analytic reionization models, see Haiman, Loeb astro-ph/9611028)

Motivations

- Probe dark ages. What's out there at $z \gtrsim 6$?
- Other ionizing sources at $z > 6.3$
  - Quasar X-ray background (Venkatesan etal astro-ph/0108168) (Oh astro-ph/0005262)
- Transition from neutral to ionized: Gradual or sudden?
  - Screening due to minihalos (Barkana & Loeb, astro-ph/0204139)
- Quasar absorbtion line studies probe single lines of sight
- Because of large opacities, it's hard to push GP trough analysis to higher redshifts.
- Information about first objects to form.

Other methods

Metal line absorbtion (Oh 2001)

Morphology of secondary anisotropies in the CMB (Gnedin & Shandarin 2002)

21 cm line (Hogan and Rees 1979)

Profile of Lyα emission line (Haiman 2002)

Gunn-Peterson trough

$$\tau(z) = \pi e^2 f_\alpha \lambda_\alpha n_{H}(z) / H(z)$$

$$\tau(z) = 3.8e5 \; x_{HI} \frac{\Omega_b h^2}{0.02} \sqrt{\frac{0.15}{\Omega_m h^2}} \left(\frac{1+z}{7.3}\right)^{1.5}$$

(Gunn & Peterson 1965)

Out to $z = 5.8$ $x_{HI} \lesssim 10^{-6}$ (Fan etal 2000, AJ, 120, 1167)

Reionization at $z = 6.3$? (Becker etal 2001, AJ, 122, 2850)
(Fan etal 2002, AJ, 123, 1247)

z_H : When H atoms first appear

z_e : When free electrons first appear

Is $z_H \equiv z_e$?

Arguments based on models in which the ionizing source formation is linked to high-σ peak collapse suggest so.

But ...

(For reference:
$$\tau_e(z) = 0.046\, x_e (1-Y_p) \frac{\omega_b}{\sqrt{\omega_m}} \left\{ \sqrt{(1+z)^3 + \frac{\Omega_\Lambda}{\Omega_m}} - \sqrt{1+\frac{\Omega_\Lambda}{\Omega_m}} \right\}$$
)

CMB polarization

$Q = (I_{11} - I_{22})/4$ $U = I_{12}/4$ $T = (I_{11} + I_{22})/4$

$$\begin{pmatrix} Q' \\ U' \end{pmatrix} = R(\psi) \begin{pmatrix} Q \\ U \end{pmatrix} \quad \perp \text{ to } \hat{n}$$

$$(Q, U) \longrightarrow (E, B) \text{ or } (\text{scalar, pseudoscalar})$$

In fourier space

$$\begin{pmatrix} Q(\vec{l}) \\ U(\vec{l}) \end{pmatrix} = R(\phi_l) \begin{pmatrix} E(\vec{l}) \\ B(\vec{l}) \end{pmatrix}$$

$$C_{El} = \frac{1}{2l+1} \sum_m |a^E_{lm}|^2$$

$$C_{Cl} = \frac{1}{2(2l+1)} \sum_m \left(a^E_{lm} a^{T*}_{lm} + a^{E*}_{lm} a^T_{lm} \right)$$

$$C_{Tl} = \frac{1}{2l+1} \sum_m |a^T_{lm}|^2$$

(A reference: Zaldarriaga PRD <u>64</u> 103001 (2001))

Reionization signatures in CMB polarization

New peaks in C_l^{EE} at low l (Zaldarriaga PRD 55, 1822, 1997)

Quadrupole Δ_{T2} at reionization → low l C_l^{EE}

$\uparrow$

Free-streaming from LSS

$$\Delta_{T2}(\eta_{R1}) \approx (\Delta_{T0} + \Psi)_{LSS}\, J_2(k\eta_{R1} - k\eta_{LSS})$$

Reionization "bump" $k \approx \frac{2}{\eta_{R1}}$

$$l_r \equiv D_A(z(\eta_{R1}))/\eta_{R1}$$

(Hu & White 1997, ApJ 479, 568)

$$l'(l'+1)\, C_{l'}^{EE} = l(l+1)\, C_l^{EE*} \left(\frac{1-e^{-\tau}}{1-e^{-\tau_*}}\right)^2 \left(\frac{\tau_*}{\tau}\right)^{(0.2-\tau_*/3)} \left(\frac{2}{l_{pivot}}\right)^{n-1} \frac{A}{A_*}$$

$$l'(l'+1)\, C_{l'}^{ET} = l(l+1)\, C_l^{ET*} \left(\frac{1-e^{-\tau}}{1-e^{-\tau_*}}\right) \left(\frac{\tau_*}{\tau}\right)^{0.2} \left(\frac{2}{l_{pivot}}\right) \frac{A}{A_*}$$

(Kaplinghat, Knox and Skordis, astro-ph/0203413)

$$l_{pivot} = (6000\,\mathrm{Mpc}\; k_{pivot}) / \sqrt{\omega_M (1+z_{R1})}$$

$$k^3 P_\Phi(k) = A\,(k/k_{pivot})^{n-1}$$

$$l' = l\,(l_r'/l_r) \quad \text{for } C_l^{EE}$$

$$l' = l\left(\frac{l_r' + .5}{l_r + .5}\right) \quad \text{for } C_l^{ET}$$

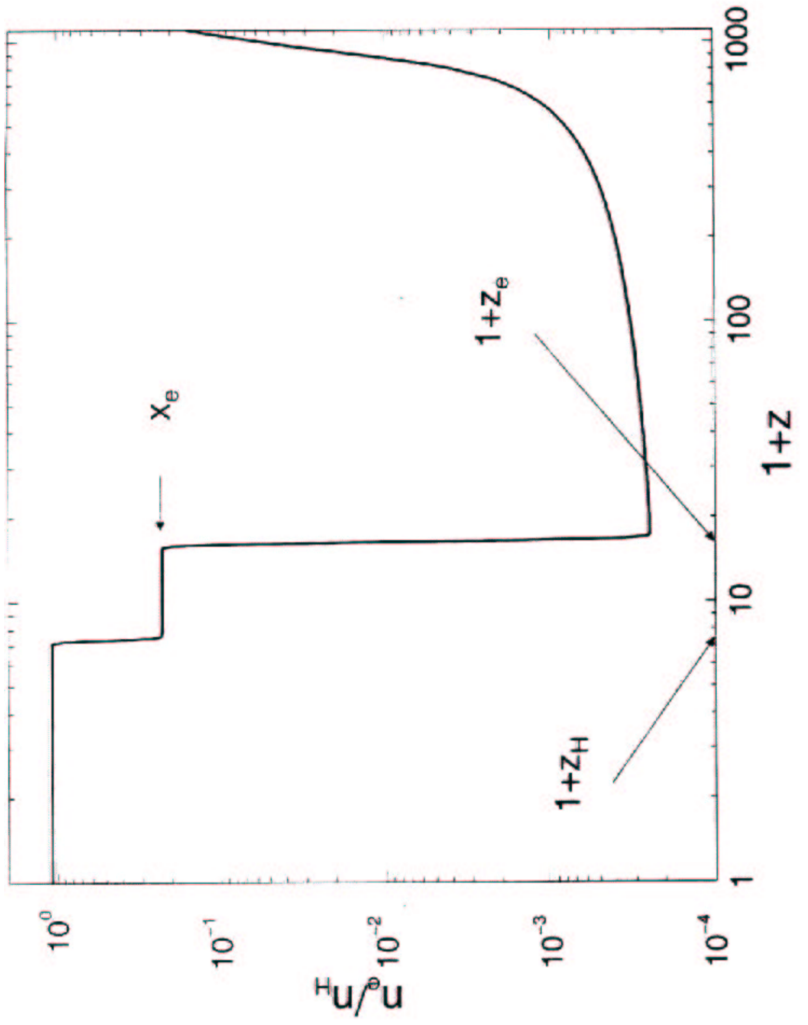


Fig. 2.— The evolution of the ionization fraction as a function of redshift (z) in a two-step reionization model. n_e and n_H are the number density of free electrons and hydrogen nuclei, respectively. The optical depth to the last scattering surface in this model is 0.05 and the epoch when electrons first appear is characterized by $z_e = 15$ and $x_e = 0.23$.

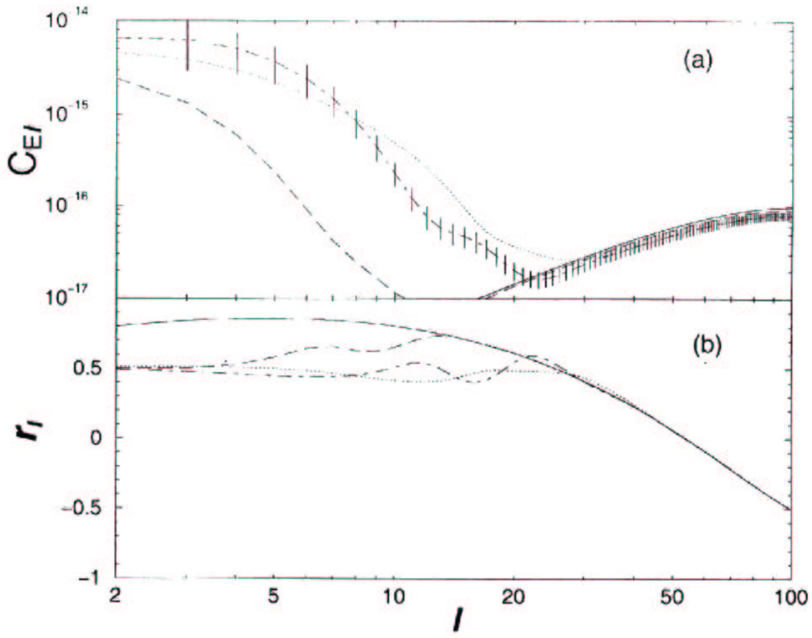
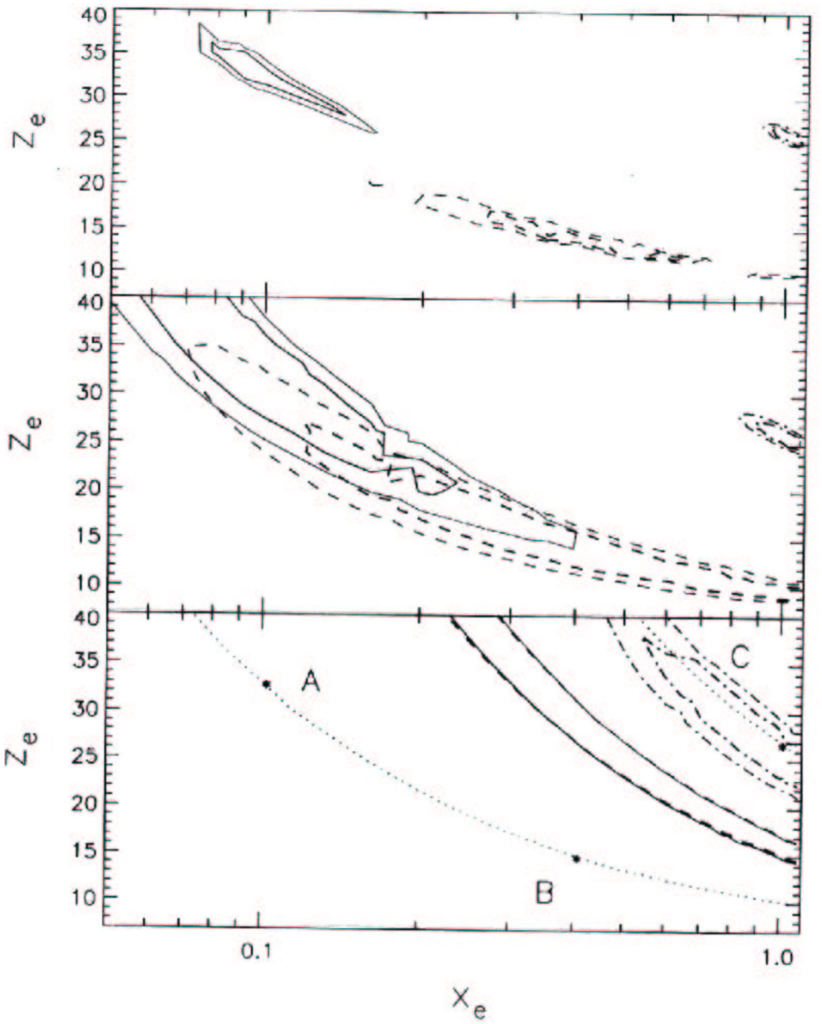


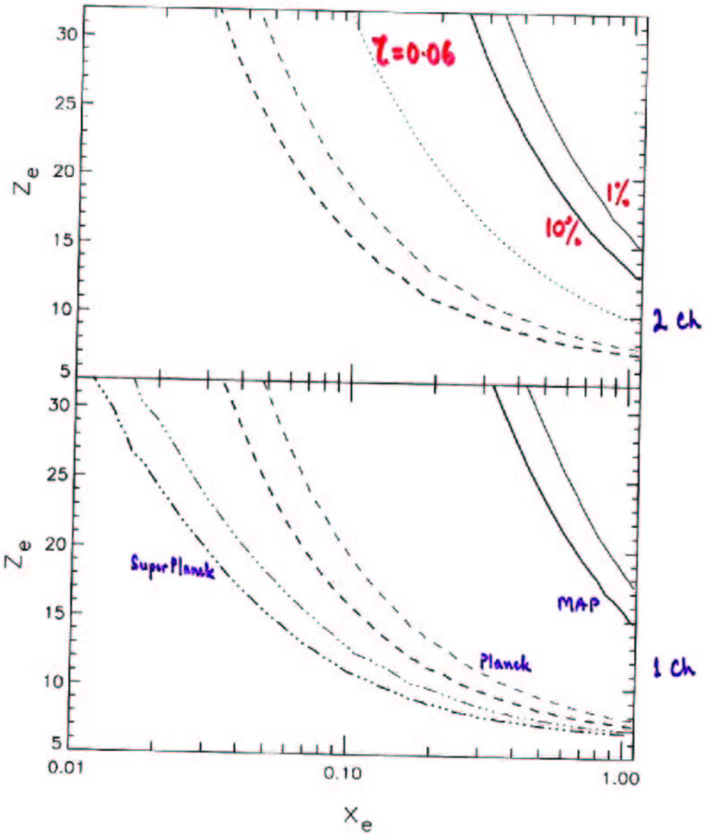
Fig. 3.— Effect of different reionization histories on the CMB anisotropy. Panel (a) shows C_{El}, and (b) shows $r_l = \mathcal{C}_{Cl}/\sqrt{\mathcal{C}_{El}\mathcal{C}_{Tl}}$. Both panels have the same set of reionization histories. The solid curve shows the result of no reionization. The other 3 curves have $z_H = 6.3$. The dashed curve has $x_e = 0$ which implies $\tau = 0.033$ (note that x_e is the ionized fraction for $z > z_H$). The dotted curve has $\tau = 0.1$ and $z_e = 30$ which requires $x_e = 0.26$. The dot-dashed curve has $\tau = 0.1$ and $z_e = 15$ which requires $x_e = 0.89$. We have added cosmic variance error bars to the $z_e = 15$ C_{El} (dot-dashed) curve.

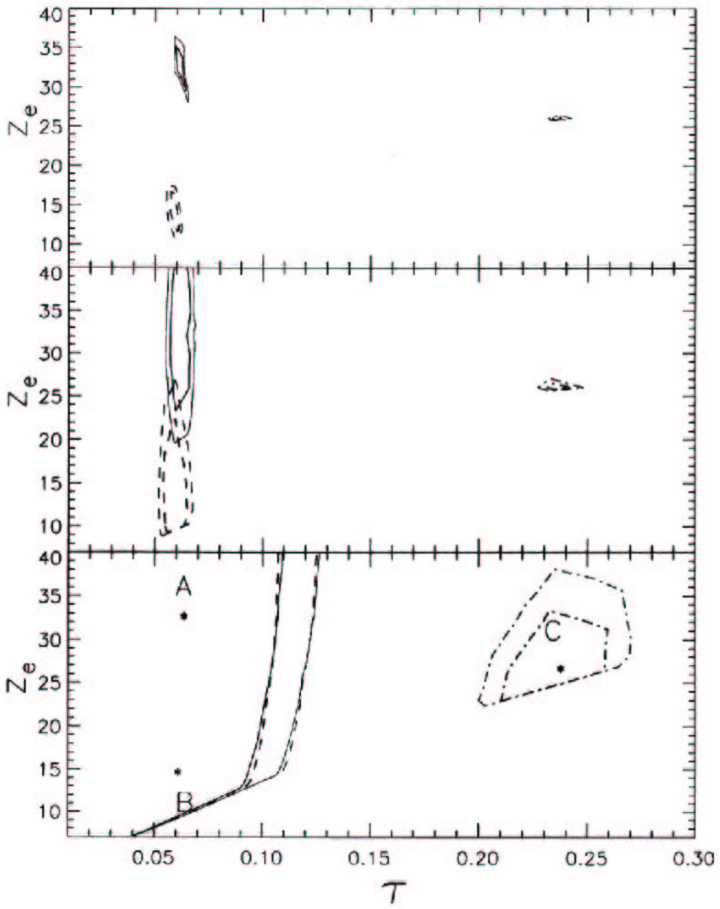


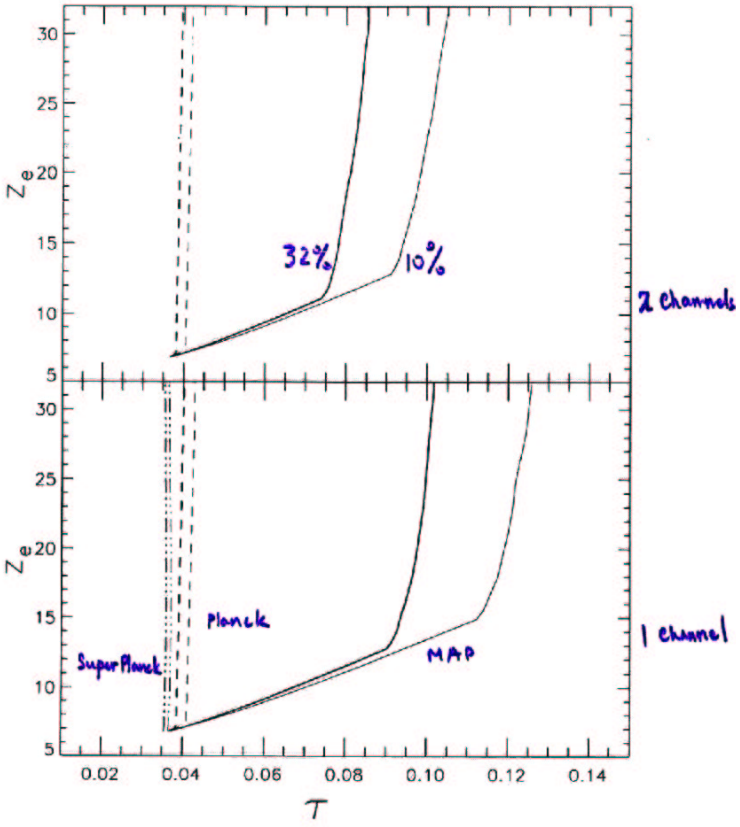
Super Planck ~ 25 × Planck

B-modes ~ $T/S \gtrsim 10^{-3}$

$V_{INF}^{1/4} \gtrsim 5 \times 10^{15}$ GeV



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10%
2 channels
Planck
SuperPlanck
MAP
1 channel
Z_e
30
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