Locating missing baryons from oxygen emission lines with DIOS (Diffuse Intergalactic Oxygen Surveyor)

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University College London
WMAP: Wilkinson Microwave Anisotropy Probe

http://lambda.gsfc.nasa.gov

NASA/WMAP Science team
WHIM and DIOS

CMB: Cosmic Microwave Background

relic thermal photons from the ancient universe

- Recombination of protons and electrons = decoupling of baryons and photons
  - Large-scale structure
  - Galaxy cluster
  - Galaxy formation

- First objects
- Light element synthesis
- Generation of quantum fluctuations
- Reionization

- Big-bang

Time history:
- 13.7 Gyr (the present)
- 0.2 Gyr
- 0.38 Myr
- 3 min
- $10^{-40}$ sec

Light element synthesis

Generation of quantum fluctuations

Recombination of protons and electrons = decoupling of baryons and photons
ancient document in cipher
- CMB all-sky map

a cipher key
- spherical harmonics

deciphered data
- temperature spectrum

grammar to understand the universe
- cold dark matter model

imprinted information
- age, geometry, and composition of the universe
Angular power spectrum of CMB temperature fluctuations observed by WMAP

\[ \frac{\delta T}{T} (\theta, \varphi) = \sum_{l,m} a_{lm} Y_{lm} (\theta, \varphi) \]

\[ C_l = \left\langle a_{lm} a^*_{lm} \right\rangle \]


\[ \Omega_K = \Omega_m + \Omega_\Lambda - 1 \]

baryon density : \( \Omega_0 h^2 \)

spectral index of primordial fluctuations : \( n_s \)

matter density : \( \Omega_0 h^2 \)

curvature of the universe
What WMAP told us:
- age of the universe: 13.7 Gyr
- universe is spatially flat
- universe reionized at 0.2 Gyr after Big-bang
- cosmic matter is dominated by dark matter
- cosmic energy is dominated by dark energy
**Results: weighing the universe**

- **baryons**: ordinary matter makes up merely 4 percent of the entire mass of the universe.

- **dark matter**: galaxies and clusters are surrounded by invisible mass an order-of-magnitude more massive than their visible part.

- **dark energy**: unknown elementary particles?

- universe is dominated by even more exotic component!

- homogeneously fills the universe (unclustered)

- repulsive force (negative pressure; equation of state: $P = -\frac{\rho}{3}$)

- Einstein’s cosmological constant?
More intriguingly, most of the cosmic baryon is also “dark”

<table>
<thead>
<tr>
<th>Component</th>
<th>Central</th>
<th>Maximum</th>
<th>Minimum</th>
<th>Grade</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Stars in spheroids</td>
<td>$0.0026 , h_{70}^{-1}$</td>
<td>$0.0043 , h_{70}^{-1}$</td>
<td>$0.0014 , h_{70}^{-1}$</td>
<td>A</td>
</tr>
<tr>
<td>2. Stars in disks</td>
<td>$0.00086 , h_{70}^{-1}$</td>
<td>$0.00129 , h_{70}^{-1}$</td>
<td>$0.00051 , h_{70}^{-1}$</td>
<td>A−</td>
</tr>
<tr>
<td>3. Stars in irregulars</td>
<td>$0.000069 , h_{70}^{-1}$</td>
<td>$0.000116 , h_{70}^{-1}$</td>
<td>$0.000033 , h_{70}^{-1}$</td>
<td>B</td>
</tr>
<tr>
<td>4. Neutral atomic gas</td>
<td>$0.00033 , h_{70}^{-1}$</td>
<td>$0.00041 , h_{70}^{-1}$</td>
<td>$0.00025 , h_{70}^{-1}$</td>
<td>A</td>
</tr>
<tr>
<td>5. Molecular gas</td>
<td>$0.00030 , h_{70}^{-1}$</td>
<td>$0.00037 , h_{70}^{-1}$</td>
<td>$0.00023 , h_{70}^{-1}$</td>
<td>A−</td>
</tr>
<tr>
<td>6. Plasma in clusters</td>
<td>$0.0026 , h_{70}^{-1.5}$</td>
<td>$0.0044 , h_{70}^{-1.5}$</td>
<td>$0.0014 , h_{70}^{-1.5}$</td>
<td>A</td>
</tr>
<tr>
<td>7a. Warm plasma in groups</td>
<td>$0.0056 , h_{70}^{-1.5}$</td>
<td>$0.0115 , h_{70}^{-1.5}$</td>
<td>$0.0029 , h_{70}^{-1.5}$</td>
<td>B</td>
</tr>
<tr>
<td>7b. Cool plasma</td>
<td>$0.002 , h_{70}^{-1}$</td>
<td>$0.003 , h_{70}^{-1}$</td>
<td>$0.0007 , h_{70}^{-1}$</td>
<td>C</td>
</tr>
<tr>
<td>7’. Plasma in groups</td>
<td>$0.014 , h_{70}^{-1}$</td>
<td>$0.030 , h_{70}^{-1}$</td>
<td>$0.0072 , h_{70}^{-1}$</td>
<td>B</td>
</tr>
<tr>
<td>8. Sum (at $h = 70$ and $z \simeq 0$)</td>
<td>0.021</td>
<td>0.041</td>
<td>0.007</td>
<td>...</td>
</tr>
</tbody>
</table>

99% of the universe is DARK

- Quite frustrating…
  We finally realized that we have not yet understood 99% of the universe at all!

- cosmological observations in the 20th century have identified previously unknown hierarchy of matter beyond the standard model of particle physics

- one needs to understand the meaning of cosmological parameters beyond mere precise estimates of their values

- from how much to why

WHIM and DIOS
hydrodynamical simulation with gas

(30h^{-1}\text{Mpc})^3 box around a massive cluster at z=0

- CDM SPH simulation

(Yoshikawa et al. 2001)

Galaxy (cold clump)

Dark matter

All gas particles

Hot gas (T>10^7K)

Warm gas (10^5K<T<10^7K)
Four phases of cosmic baryons


- **Condensed:** $n > 1000$, $T < 10^5 K$
  - Stars + cold intergalactic gas

- **Diffuse:** $n < 1000$, $T < 10^5 K$
  - Photo-ionized intergalactic medium
  - Ly$\beta$ absorption line systems

- **Hot:** $T > 10^7 K$
  - X-ray emitting hot intra-cluster gas

- **Warm-hot:** $10^5 K < T < 10^7 K$
  - Warm-hot intergalactic medium (WHIM)
Emission lines of oxygen in WHIM

O\text{VII} (561eV, 568eV, 574eV, 665eV), O\text{VIII} (653eV)

- **Why oxygen emission lines?**
  - Most abundant other than H and He
  - Good tracers of gas around \( T=10^6\sim10^7 \) K
  - No other prominent lines in \( E=500-660eV \)
  - Not restricted to regions towards background QSOs

- **systematic WHIM survey**
**DIOS: Diffuse Intergalactic Oxygen Surveyor**

A Japanese proposal of a dedicated X-ray mission to search for dark baryons

- **PI: Takaya Ohashi** (Tokyo Metropolitan Univ.)
  - + Univ. of Tokyo, JAXA/ISAS, Nagoya Univ., Tokyo Metro. Univ.
- A dedicated small satellite with cost < 40M USD.
- Proposed launch in **2008 (not yet approved)**.
- Unprecedented energy spectral resolution: \( \Delta E = 2\text{eV} \) in soft X-ray band (0.1-1keV)
- Aim at detection of \( \sim 30 \) percent of the total cosmic baryons via **Oxygen emission lines**.
Searching for dark baryons with DIOS
(Diffuse Intergalactic Oxygen Surveyor)

Mock simulations

Univ of Tokyo:
K. Yoshikawa
Y. Suto

JAXA/ISAS:
N. Yamasaki
K. Mitsuda

Tokyo Metropolitan Univ.:
T. Ohashi

Nagoya Univ.:
Y. Tawara
A. Furuzawa

PASJ 55 (2003) 879
astro-ph/0303281, 0402389
Light-cone output from simulation

- **Cosmological SPH simulation** in $\Omega_m=0.3$, $\Omega_\Lambda=0.7$, $\sigma_8=1.0$, and $h=0.7$ CDM with $N=128^3$ each for DM and gas (Yoshikawa, Taruya, Jing, & Suto 2001)

- **Light-cone output from $z=0.3$ to $z=0$** by stacking 11 simulation cubes of $(75h^{-1}\text{Mpc})^3$ at different $z$

- **5 $\times$ 5 FOV mock data** in 64x64 grids on the sky

- 128 bins along the redshift direction ($\Delta z=0.3/128$)
Surface brightness on the sky

Bolometric X-ray emission

OVII and OVIII line emission

WHIM and DIOS
Metallicity models

Oxygen enrichment scenario in IGM

Type-II SNe $\rightarrow$ galaxy wind merging $\rightarrow$ metal pollution in IGM

Metallicity of WHIM is quite uncertain

Adopted models for metallicity distribution

**Model I**: uniform and constant
$Z = 0.2 \ Z_{\text{solar}}$

**Model II**: uniform and evolving
$Z = 0.2 \ Z_{\text{solar}} \left(\frac{t}{t_0}\right)$

**Model III**: density-dependent (Aguirre et al. 2001)
$Z = 0.005 \ Z_{\text{solar}} \left(\frac{\rho}{\rho_{\text{mean}}}\right)^{0.33}$ (galactic wind driven)

**Model IV**: density-dependent (Aguirre et al. 2001)
$Z = 0.02 \ Z_{\text{solar}} \left(\frac{\rho}{\rho_{\text{mean}}}\right)^{0.3}$ (radiation pressure driven)
Creating Mock spectra from light-cone simulation output

- For a given exposure time,
  - convolve the emissivity according to gas density and temperature in $(5 \frac{\Delta}{64})^2$ pixels over the lightcone
- Add the Galactic line emission (McCammon et al. 2002)
- Add the cosmic X-ray background contribution (power-law+Poisson noise)
- Then statistically subtract the Galactic emission and the CXB and obtain the residual spectra for $\Delta E=2\text{eV}$ resolution.
Simulated spectra: region A

Shallow survey observation with the DIOS field-of-view (16^2 pixels)

A

$0.94 \times 0.94 = 0.88 \text{ deg}^2$

$T_{\text{exposure}} = 3 \times 10^5 \text{ sec}$
Simulated spectra: region D

Deeper observation of targeted fields with DIOS (5² pixels)

$19' \times 19' = 0.098 \text{ deg}^2$

$T_{\text{exposure}} = 10^6 \text{ sec}$
Simulating the local universe

- Simulation by Dolag et al. (astro-ph/0310902)
  - Initial condition: smoothing the observed galaxy density field of IRAS 1.2 Jy galaxy survey (over $5h^{-1}$Mpc), linearly evolving back to $z=50$
  - adiabatic run of dark matter and baryons (without cooling or feedback) in a canonical $\Lambda$CDM model

- Locating the WHIM in the local universe
Simulated local universe vs. 2MASS map

Soft X-ray map of the simulated local universe (Yoshikawa et al. 2004)
Tour of the simulated local universe

Klaus Dolag (2003)
Simulated gas distribution on the supergalactic plane

- Coma
- Hydra
- Centaurus
- Virgo
- A3627
- Pisces-Perseus

Gas temperature

Gas density

(adopted) metallicity
Mock observation of X-ray filament extending around simulated A3627

WHIM and DIOS

1  1  1  FOV
Mock observation of simulated Coma

WHIM and DIOS
a small clump in front of simulated Coma

\[ \sim 10 \pm (\sim 5h^{-1}\text{Mpc}) \]
away from los toward Coma

1 1 1 FOV
Soft X-ray excess of Coma

- XMM-Newton observations of the outskirts of Coma (Finoguenov, Briel & Henry 2003, A&A 410, 777)
- X-ray filament of 0.2keV warm gas?

Simulated observation

(T=0.2keV)

(1/8) FOV
Fraction of cosmic baryons detectable via oxygen emission

**O VII**

**O VIII**

DIOS detection limit

\(T_{\text{exp}} = 10^5 \text{s}; \ S/N = 10\)
Locating Warm-Hot Intergalactic Medium via Oxygen emission lines

- Mock spectral observations of oxygen emission lines (Yoshikawa et al. 2003, 2004)
- **DIOS will be able to locate $\sim 30$ percent of the total cosmic baryons directly**
  - $\Delta E=2\text{eV}, \ S_{\text{eff}} \Omega =100 \ [\text{cm}^2 \text{deg}^2], \ T_{\exp }=10^5 \text{s}, \ S/N=10$
  - flux limit $= 6 \times 10^{-11} \ [\text{erg/s/cm}^2/\text{str}]$
- Things remain to be checked
  - Validity of the collisional ionization equilibrium?
  - Strategy to quantify the fraction of WHIM; targeted observations vs. blank survey
  - Sciences with DIOS other than WHIM search
Oxygen emission in supergalactic coordinates

**O**\textsubscript{VII}

**O**\textsubscript{VIII}

WHIM and DIOS

soft X-ray
Expected S/N for \textsl{OvIII} line

For a detector of $S_{\text{eff}} \Omega = 100 \text{ cm}^2 \text{deg}^2$ and $\Delta E = 2\text{eV}$

\[ T_{\exp} = 10^5 \text{sec} \]
\[ T_{\exp} = 10^4 \text{sec} \]
\[ T_{\exp} = 10^6 \text{sec} \]
### Oxygen lines

<table>
<thead>
<tr>
<th></th>
<th>Transition</th>
<th>Energy (eV)</th>
<th>Wavelength (Å)</th>
</tr>
</thead>
<tbody>
<tr>
<td>OVI</td>
<td>$1s^2 - 1s2s \left(^3S_1\right)$</td>
<td>561</td>
<td>22.1</td>
</tr>
<tr>
<td>OVI</td>
<td>$1s^2 - 1s2p \left(^3P_1\right)$</td>
<td>568</td>
<td>21.8</td>
</tr>
<tr>
<td>OVI</td>
<td>$1s^2 - 1s2p \left(^1P_1\right)$</td>
<td>574</td>
<td>21.6</td>
</tr>
<tr>
<td>OVI</td>
<td>$1s - 2p \left(Ly_β\right)$</td>
<td>653</td>
<td>19.0</td>
</tr>
<tr>
<td>OVI</td>
<td>$1s^2 - 1s3p$</td>
<td>665</td>
<td>18.6</td>
</tr>
<tr>
<td>OVI</td>
<td>$1s - 3p \left(Ly_δ\right)$</td>
<td>775</td>
<td>16.0</td>
</tr>
<tr>
<td>NeI X</td>
<td>$1s^2 - 1s2s \left(^3S_1\right)$</td>
<td>905</td>
<td>13.7</td>
</tr>
<tr>
<td>NeI X</td>
<td>$1s^2 - 1s2p \left(^3P_1\right)$</td>
<td>914</td>
<td>13.6</td>
</tr>
<tr>
<td>NeI X</td>
<td>$1s^2 - 1s2p \left(^1P_1\right)$</td>
<td>921</td>
<td>13.5</td>
</tr>
</tbody>
</table>
Requirements for detection

- **Good energy resolution** to identify the emission lines from WHIM at different redshifts
  - $\Delta E < 5\text{eV}$ — X-ray calorimeter using superconducting TES (Transition Edge Sensor)
- **Large field-of-view** and effective area for survey
  - $S_{\text{eff}} = 100\text{cm}^2$, $\Omega = 1\text{deg}^2$ — 4-stage reflection telescope
- Angular resolution is not so important (but useful in removing point source contaminations)

\[
\theta \approx 1^\circ \left( \frac{600 \, h^{-1}\text{Mpc}}{D} \right) \left( \frac{L}{10 \, h^{-1}\text{Mpc}} \right)
\]
## DIOS: instrument summary

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Area</td>
<td>&gt; 100 cm²</td>
</tr>
<tr>
<td>Field of View</td>
<td>50’ diameter</td>
</tr>
<tr>
<td>$S \Omega$</td>
<td>~100 cm²deg²</td>
</tr>
<tr>
<td>Angular Resol.</td>
<td>3’ (16² pixels)</td>
</tr>
<tr>
<td>Energy Resol.</td>
<td>2 eV (FWHM)</td>
</tr>
<tr>
<td>Energy Range</td>
<td>0.1 - 1 keV</td>
</tr>
<tr>
<td>Life</td>
<td>&gt; 5 yr</td>
</tr>
</tbody>
</table>

Mechanical coolers + ADR: < 100 mK
Initial cooling ~ 3 months
**DI OS: spacecraft**

<table>
<thead>
<tr>
<th>Weight</th>
<th>Total</th>
<th>~ 400 kg</th>
</tr>
</thead>
<tbody>
<tr>
<td>Payload</td>
<td>~ 280 kg</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Size</th>
<th>Launch</th>
<th>1.2 m ( \pm ) 1.45 m</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>In orbit</td>
<td>5.85 m ( \pm ) 1.45 m</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Attitude</th>
<th>Control</th>
<th>3-axis bias momentum wheel, Sun pointing in 1 axis</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Accuracy</td>
<td>( \pm ) 10 arcsec</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Power</th>
<th>Total</th>
<th>450 W</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Payload</td>
<td>250 W</td>
</tr>
</tbody>
</table>

Altitude: ~ 550 km
Inclination: 30°
Rotation period: 95 min
DIOS: comparison with other missions

- Very high sensitivity ($S\Omega$ and $\Delta E$) in detecting oxygen emission lines
- Intensity ratios of the lines reveal the temperature and ionization condition of WHIM
Physical properties of the probed baryons

Each symbol indicates the temperature and the over-density of gas at each simulation grid (4x4 smoothed pixels over the sky and \( \Delta z=0.3/128 \))

- \( \bigcirc \) \( S_x > 3 \times 10^{-10} \) [erg/s/cm\(^2\)/sr]
- \( \bigotimes \) \( S_x > 6 \times 10^{-11} \) [erg/s/cm\(^2\)/sr]
- \( \triangle \) \( S_x > 10^{-11} \) [erg/s/cm\(^2\)/sr]
Dependence on the metallicity model

- We have adopted model I (constant 0.2 solar metallicity) so far
- Density-dependent metallicity models show stronger emission lines.
- WHIM will be unambiguously detected with our proposed mission