Circumgalactic O VI: origins, distribution, kinematics, ionisation states and evolution from $z = 3-0$

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Simons Symposia “Galactic Superwinds”, May 10, 2018

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Origins of O VI

- Gas cooling from higher temperature through the $T \sim 10^{5.5}$ K (Heckman+2002; McQuinn & Werk 2017)
  - Condition: $10 < nT < 100$ cm$^{-3}$ K (i.e. the “high-pressure scenario”)

- Photoionized by the UV Background (Stern+2018)
  - Condition: low pressure $nT \sim 1$ cm$^{-3}$ K (i.e. the “low-pressure scenario”)
Evolution $z = 3$ to 0

- Larger column density at higher $z$
- Contribution of mergers and satellites
- Gas traced by OVI outflowing, decreasing speed with time
- “Jump” at $z = 1.5$ and 0.5 because of UVB change

1 Mpc x 1 Mpc, N (OVI) evolution
OVI properties in Eris: distribution

- \( N_{\text{OVI}} = 10^{14} - 10^{15} \text{ cm}^{-2} \) beyond \( R_{\text{vir}} = 230 \text{ kpc} \)

- \( \text{Cf} (N > 10^{14.15} \text{ cm}^{-2}) = 90\% \), similar to COS (91\% for SF galaxies, Werk+2013)

- No strong evolution from \( z = 3 \) to 0 within \( \sim 100 \text{ kpcs} \)
3D mass distribution of OVI and O

$z = 3, 2, 1, 0.5, 0$

- 3D OVI mass distribution peaks around $r \sim R_{\text{vir}}$
- Significant increase from $z = 0.5$ to $z = 0$: effect of UVB
Collisional ionisation vs. Photoionisation

• \(z=0\), collisional ionisation \((\text{within } R_{\text{vir}})\) + photoionisation \((> R_{\text{vir}})\)

• \(z=3\), collisional ionisation
Impact of the UV background

• Ionising background decrease rapidly at $z < 1$, e.g., decrease 5 x from $z = 0.5$ to $z = 0$

• If $z = 0.5$ UVB used for the $z = 0$ snapshot, $M(<2R_{\text{vir}}) = 4 \times 10^6 \, M_{\odot}$ instead of $1.5 \times 10^7 \, M_{\odot}$

• Strong UV background ionise oxygen to OVII or OVIII
Collisional ionisation vs. Photoionisation

- similar pressure profile at $z < 1$ ($M_h \times 10^{11.5} M_{\odot}$ from $z = 2$ to 1), gas shock heated; but high pressure profile already there at $z = 2-3$ from galactic outflows

- Gas predominately collisional ionised down to $z = 1$; photoionisation becomes important beyond $\sim 150$ kpc, at $z \sim 0$ photoionisation important for outer halo
How is the diffuse warm-hot halo build up with time?

- $T \sim 10^5 - 10^6$ gas exist within $R_{\text{vir}}$ as early as $z = 3-4$ mainly due to feedback.

- Two main origins of the warm-hot gas in Eris: 1. SN feedback energy; 2. shock heating from accretion (Sokołowska et al. 2017)
Heating source: feedback or gas accretion?

- 25 particles \( f_{OVI} > 0.3 \) \( f_{OVI}^{\text{max}} \), track back to \( z = 3 \)

- Heating to \( T > 10^6 \) K, cools through \( T \sim 10^{5.5} \) K window

- Heating and OVI increase occurs at small radii — feedback rather than accretion

Shock heated
Cooling time

- $T \sim 10^{5.5} \text{ K}, n = 10^{-4} \text{ cm}^{-3}$

- Cooling time $t_{\text{cool}} > 1$ Gyr (with no metal cooling)

- With metal cooling $t_{\text{cool}} \sim$ a few 100 Myr
Analytical model

\[ N_{\text{OVI}} = \frac{f_{\text{OVI}} [f_{\text{O}}]_\odot Z}{\pi R^2 \times \mu_i m_p} \times \dot{M} \times t_{\text{OVI}}, \]

\[ = 2 \times 10^{14} \text{ cm}^{-2} R_{200k}^{-2} \left( \frac{\dot{M}}{100 \text{ } M_\odot \text{ yr}^{-1}} \right) \times \left( \frac{Z}{0.3} \right) \left( \frac{t_{\text{OVI}}}{100 \text{ } \text{Myr}} \right), \]

McQuinn & Werk (2018)

- \( t_{\text{cool}} \sim \) a few Gyr \( \rightarrow \) \( \dot{M} / \dot{t} \) needs to be \( \sim 10 \) \( M_\odot / \text{yr} \), easily satisfied at \( z = 2-3 \);

- At \( z = 0 \), \( \dot{M} / \dot{t} \sim 2-3 \) \( M_\odot / \text{yr} \), \( N_{\text{OVI}} \) at larger radii (from collisional ionisation only) may be low;

- With metal cooling, \( t \sim \) few 100 Myrs, larger \( \dot{M} / \dot{t} \) is necessary
E2K: the degeneracy between SF, feedback and cooling

- E2K: stronger feedback, metal cooling, metal + thermal diffusion
- OVI distribute to Rvir with high column but declines at r > Rvir

box size: 500 pkpc

\[
\text{log } N_{\text{OVI}} = f(b/R_{\text{vir}}, z)
\]

- Tumlinson et al. (2011)
- Prochaska et al. (2011), sub $L^*$
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Impact of local radiation on cooling

- x-ray radiation from old stars significantly changing the cooling and heating rate

Cantalupo 2010; Gnedin & Hollon 2012
Kannan+2014
O VI Kinematics: non-thermal broadening

Preliminary