arXiv:2404.05725v1

The MOSDEF Survey: Properties of Warm Ionised Outflows at $z = 1.4 - 3.8$

Andrew Weldon,[1★] Naveen A. Reddy,[1] Alison L. Coil,[2] Alice E. Shapley,[3] Brian Siana,[1] Mariska Kriek,[4] Bahram Mobasher,[1] Zhiyuan Song,[1] Michael A. Wozniak,[1‖]

ABSTRACT

We use the large spectroscopic data set of the MOSFIRE Deep Evolution Field survey to investigate the kinematics and energetics of ionised gas outflows. Using a sample of 598 star-forming galaxies at redshift $1.4 < z < 3.8$, we decompose Hα and [O III] emission lines into narrow and broad components, finding significant detections of broad components in 10% of the sample. The ionised outflow velocity from individual galaxies appears independent of galaxy properties, such as stellar mass, star-formation rate (SFR), and star-formation-rate surface density (Σ_{SFR}). Adopting a simple outflow model, we estimate the mass-, energy- and momentum-loading factors of the ionised outflows, finding modest values with averages of 0.33, 0.04, and 0.22, respectively. The larger momentum- than energy-loading factors, for the adopted physical parameters, imply that these ionised outflows are primarily momentum-driven. We further find a marginal correlation (2.5σ) between the mass-loading factor and stellar mass in agreement with predictions by simulations, scaling as $\eta_m \propto M_\star^{-0.45}$. This shallow scaling relation is consistent with these ionised outflows being driven by a combination of mechanical energy generated by supernovae explosions and radiation pressure acting on dusty material. In a majority of galaxies, the outflowing material does not appear to have sufficient velocity to escape the gravitational potential of their host, likely recycling back at later times. Together, these results suggest that the ionised outflows traced by nebular emission lines are negligible, with the bulk of mass and energy carried out in other gaseous phases.

Key words: galaxies: evolution – galaxies: kinematics and dynamics – galaxies: ISM – ISM:jets and outflows

[1]. Introduction

- The influence of galactic outflow:
  - suppressing star-formation,
  - modulating the metallicity within galaxies,
  - enriching the circumgalactic medium (CGM) and intergalactic medium (IGM) with metals
- The process by which outflow affects galaxies is complex.
- There is not much research on outflow at high redshift.

➔ Need to constrain how the properties of the outflow affect galaxy

[2]. Data and measurements

- spectroscopic data set from MOSFIRE Deep Evolution Field (MOSDEF) survey
- 598 star-forming galaxies at redshift $1.4 < z < 3.8$
- search for ionised gas outflows by decomposing Hβ, [O iii]$\lambda\lambda$4960,5008 and Hα, [N ii]$\lambda\lambda$6550,6585 into narrow Gaussian components
- Find relationship mass loading factor with stellar mass, star formation rate (SFR), star-formation-rate surface density (ΣSFR= SFR/($2\pi R_E^2$)), and specific star-formation rate surface density (ΣsSFR = SFR/($2\pi R_E^2 M_\star$)

[3]. How to find outflow?

- Narrow components: quiet, regular gas movement within the galaxy.
- Broad components: fast, chaotic movement, like outflowing gas.
- Finding the broad component by measuring the FWHM of the emission lines
- The low signal-to-noise ratio (S/N) of galaxy spectra limits the detection of broad components. To address this, combined data from multiple galaxies to create a composite spectrum

[4]. Results

4.1 Find outflow fata

The MOSDEF dataset used in the study included a total with [O iii] or Hα detection, of which 62 galaxies (10%) had significant of 598 star forming galaxies broad components.

- Number of galaxy with broad components in [O iii]: 39 (10%)
- Number of galaxy with broad components in Hα: 33 (7%)

4.2 Comparison of the physical properties of galaxies with and without ionized outflows

- Star formation rate (SFR) and SFR surface density (ΣSFR):
  - Ionized outflows are mainly observed in galaxies with high star formation activity.
- ΣSFR threshold:
  - Almost all galaxies where outflows have been detected have a $\Sigma SFR \geq 0.05\ M_\odot\ yr^{-1}\ kpc^{-2}$.
  - This is consistent with the theory (Heckman, 2002) that above this value, the ionized outflow overcomes the gravitational field of the galaxy and is ejected outward.

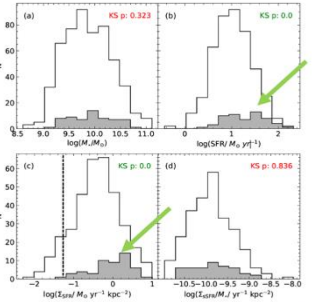

Figure 3. The distribution of various galactic properties. Panel (a): stellar mass, Panel (b): SFR, Panel (c): Σ_{SFR}, Panel (d): Σ_{sSFR}. Solid grey and open bars represent the 62 galaxies with detected broad components and the remaining galaxies, respectively. The p-value of a KS test between galaxies with a broad component and the remaining galaxies is shown in the upper corners of each panel. The vertical dashed line in panel (c) marks the Σ_{SFR} threshold proposed by Heckman (2002) for launching an outflow.

4.3 Comparison of galaxy features and Vmax derived from [O III] and Hα

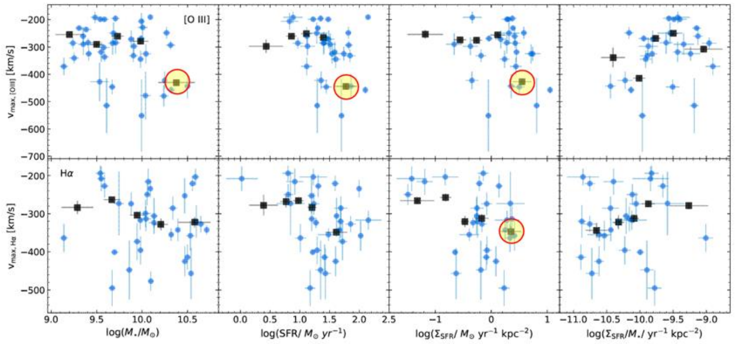

Figure 4. Maximum outflow velocity versus various galactic properties. *left*: stellar mass, *left centre*: SFR, *right centre*: Σ_{SFR}, *right*: Σ_{sSFR}. Top (bottom) rows are plotted versus [O III] (Hα) V_{max}. Individual galaxies are shown as blue circles, while results from composite spectra are shown as black squares.

- Individual galaxy analysis (blue circles)
  - significant correlation is not found
- Composite spectrum analysis (black squares)
  - In the highest stellar mass, SFR, and ΣSFR, the Vmax values calculated from [O III] show significantly higher velocities than those at the lowest.
  - Similarly, the Vmax values derived from Hα show faster velocities in the high ΣSFR region and faster velocities in the low ΣsSFR region.

➔ [O III] is emitted appears to be more compact than the H II region, because [O II] requires higher ionization energies than H I (35 eV and 13.6 eV, respectively).

4.4 Mass-loading factor (η_m)

: The mass removed by the outflow divided by the mass of the star that formed. This is used as a diagnostic tool for outflow efficiency.

$$\eta_m = \frac{\dot{M}_{out}}{SFR}$$

- Relation between η_m and $M_\star$
  - The lower mass of galaxy, the higher η_m value
  - In the $\log(M_\star/M_\odot)$ = 9 – 10.7 range, η_m decrease ~ 0.6 (= same with ◆ Llerena et al. 2023)
  - Mass loading factor of ★ Marasco et al. (2023) data is significantly lower compared to the MOSDEF data.

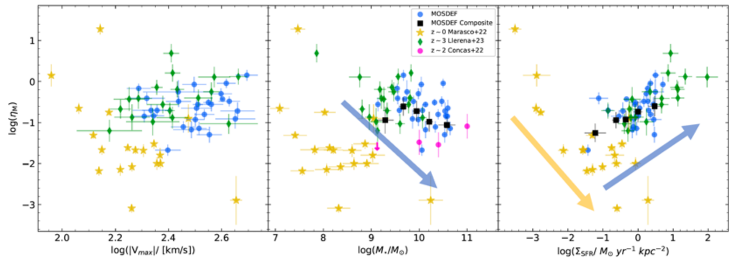

Figure 5. Mass-loading factor versus various galactic properties, compared with values from the literature. *left*: log(|V$_{max}$|), *centre*: log($M_\star$), *right*: log(Σ_{SFR}). Individual MOSDEF galaxies are shown as blue circles, while results from composite spectra are shown as black squares. Markers show observational results including low-mass star-forming galaxies at $z \sim 3$ from Llerena et al. (2023, green diamounds), local starburst dwarf galaxies from Marasco et al. (2023, yellow stars), and composites of $z \sim 2$ star-forming galaxies from Concas et al. (2022, pink circles).

- Relation between η_m and Σ_{SFR}
  - The higher Σ_{SFR} of galaxy, the higher η_m value
  - In the $\log(\Sigma_{SFR}/M_\odot\ yr^{-1}\ kpc^{-2})$ = -1.4 – 0.7 range, η_m increase 1.8 dex (= same with ◆ Llerena et al. 2023)
  - Conversely, ★ Marasco et al. (2023) found a strong negative correlation between ΣSFR and η_m in their sample.
    - Possible reason of difference result with ★ Marasco et al. (2023):
      - This paper and ◆ Llerena et al. 2023: $\Sigma SFR = SFR/(2\pi R_E^2) \rightarrow \Sigma SFR \propto R_E^{-2}$ & $\eta_m \propto R_E^{-1}$
      - Marasco et al. (2023) derived η_m using outflow radius measured directly from the sample (independent of the effective radius).

4.5 Comparison with escape velocity

- The outflow observed in the [O III] emission line: outflow of 4 galaxies can escape
- The outflow observed in the Hα emission line: outflow of all galaxies remain inside the gravitational field, unable to escape.
- Interestingly, the shallow gravitational fields (=low stellar mass) is not related to the escape of galactic outflow

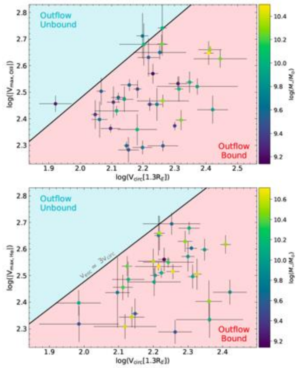

Figure 8. Maximum ionised outflow velocity as a function of circular velocity. *Top*: [O III] *Bottom*: Hα. The line denotes the gas velocity required to escape the gravitational potential assuming an isothermal gravitation potential that extends to a maximum radius of r_{max}, see Equation 9. Outflowing gas above $3v_{circ}$ ($r_{max}/r = 33$) likely has enough velocity to escape, while below $3v_{circ}$ the gas is likely retained. Objects are colour coded according to their stellar mass.

[5]. Conclusion

- In individual galaxies, the maximum ionization outflow speed: not significant relation.
- In the composite spectra, the maximum ionization outflow speed: a trend for Vmax in regions with higher galaxy physical properties.
- The mass loading factor (η_m): a weak correlation with galaxy mass ($M_\star$) and scales as $\eta_m \propto M_\star^{-0.45}$.
- For [O iii], maximum outflow speed of 4 galaxies is greater than the escape velocity from the host galaxy's gravitational potential, but none for Hα.

--> suggests that ionized outflow gas often resides in galaxies.