Neutral outflows in high-redshift dusty galaxies

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English Summary

Humans and the Universe

Imagine coming into consciousness for the first time at age 30. Thrust into a fully formed adult body and left to work out not just what you are but how you came to be.

Millions of years ago Humanity found itself in this conundrum; awakening to find ourselves on a fully formed planet, in a fully formed solar system, moving through a fully formed Grand Design Spiral Galaxy attached to an established Galaxy group floating through a cosmic web of gas, dust, that mysterious invisible dark matter stuff and other galaxies stretching to the farthest reaches of the observable universe.

It's a lot...

.. but we've made it pretty far. Many areas of research dedicate themselves to uncovering how we came to be, but with astronomy and astrophysics we have begun to understand how the entire Universe and its innards came to be. We began with our eyes, simply tracking the bright lights, or lack thereof, in the sky. As our technology advanced, we aided our gaze with telescopes, capable of magnifying and capturing faint light travelling from distant places in the Universe to Earth. It is with these advancements that we have discovered that there is a lot more to the sky than our human eyes can see, beyond the planets in our solar system and the stars in our Milky Way Galaxy. We taught our telescopes to see light bluer and redder than our human eyes can see by collecting X-rays, microwaves, infrared light, radio waves and everything in between on what we call the electromagnetic spectrum. The full landscape of the universe from the hottest most energetic plasma to the darkest coldest cloaks of dust is available to us. We have found countless more galaxies beyond our Milky Way, each with its own unique shape, colour, age, neighbourhood and history.

In the study of galaxy formation and evolution, we aim to understand how galaxies came to be and how they grew into the beauties they are today. Just like ourselves, they require homes to build their lives in (dark matter halos) and food to grow big and strong (gas). As young galaxies, their growth is rapid and explosive, building up their gas reservoirs and transforming them into stars or feeding their supermassive black holes. Like all teens, this growth spurt is messy, resulting in energetic outbursts from stars and accreting black holes. This pushes much of the gas fed to it back into the parental cosmic web.

It turns out this cosmic food fight has massive implications for the development and eventual retirement of galaxies in our Universe. Ejected gas can no longer be used to form new stars or continue to feed black holes. Because the gas that is ejected is nearby star-forming regions or active black holes, the galaxy also loses its most enriched gas which has been partially processed and is now metal-rich. Similarly, gas is preferentially lost from the central regions of galaxies where star formation and black hole activity are most extreme. This removes the guts of the galaxy which can, if it is not ejected fast enough, flow like a fountain to the outer edges of the galaxy, rearranging the mass distribution. In fact, without outflows, we would not have pancake-shaped galaxies like our Milky Way.

Capturing light from these outflows at different sections of the electromagnetic spectrum has revealed a complex mixture of gas travelling at different speeds, angles, densities and temperatures. The hottest gas is found to escape the host galaxies the fastest but does not carry out much of the mass. Most of the mass is instead locked up in cold neutral gas which is ejected or swept up at slower speeds. Cold gas, particularly molecular gas, is also the material from which stars are directly formed, thus making it a very interesting component to investigate the impact outflows have on their host galaxy's evolution.

The Atacama Large Millimeter/submillimeter Array (ALMA) is one such telescope that is tuned to capture the millimetre wave light associated with cold gas and dust. Its 66 radio dishes sit at 5058.7 m above sea level in one of the driest places on Earth, the Atacama desert in northern Chile. This is the largest and most sensitive telescope of its kind and yet, capturing the faint light associated with galaxy outflows remains difficult. It becomes even more difficult the farther we want to look away, but of course, that's where all the fun is.

We have learnt that the most massive galaxies in the universe formed early, grew explosively and retired young. These are also the galaxies where we expect the most exciting and impactful outflows. To observe them during their growth spurt we therefore have to look very far away where light has had to travel for billions of years to reach us. This allows us to see into the Universe's past when star formation and black hole activity were at their most extreme. So how do we observe these distant wisps of gas?

Enter Kirsty.

This thesis

In this thesis, we go looking for the naughtiest teen galaxies in our Universe, spewing the cold remains of their thoughtfully prepared dinner. We target two epochs in the universe: Cosmic Dawn and Cosmic Noon where we expect to find the biggest outflows driven by star formation and black hole activity. To observe these distant outflows we take advantage of two phenomena: strong gravitational lensing and molecular absorption lines.

Strong gravitational lensing occurs when two objects lie along the same line of sight looking out from our position in the universe. The light from the background source gets bent around the foreground object due to a distortion in space-time caused by its huge mass. This has two effects, 1) the background source appears larger and 2) brighter than it really is. This magnification means that our telescopes are able to observe the source at higher spatial resolution and in less time to detect its light.

With molecular absorption lines, we can trace neutral gas reservoirs sitting between us and a bright background emission source. In this sense, we see the shadow of the gas as it blocks out the light behind it. Fortunately, in these heavily star-forming galaxies, there is a lot of dust and this dust absorbs the radiation from stars or black holes within the galaxy and re-radiates it throughout the infrared section of the electromagnetic spectrum. This is very bright and trivial to detect even at high redshift in these galaxies. Thus, instead of trying to detect the very weak signatures of an outflow's emission, we can instead look for the shadow of it imprinted on the bright background dust continuum.

Now that all our tricks are revealed, this is what we did:

- **Chapter 2**
  In this chapter, we take a deep dive into a luminous gravitationally lensed star-forming galaxy $\sim$ 3 Gyrs after the Big Bang ($\sim$ 10.4 Gyrs ago). We combine images of dense molecular gas, dust and stars and reconstruct them into what we believe the galaxy would

look like if the foreground lensing galaxy was not there. We find a heavily star-forming galaxy with a massive neutral gas outflow in its circum-galactic medium. We see the outflow as a shadow imprinted on light emitted by the host galaxy's dust component. Since we observe the universe in only two spatial and one velocity dimensions with our telescopes, we must make some assumptions about the outflow's geometry. We find that if we explore the full possible parameter space of our assumed outflow properties, the ejection mechanism (feedback from stars vs black holes) of the outflow, and the impact on its host galaxy and surroundings drastically vary from one extreme to the other.

- **Chapter 3**
  This chapter studies a sample of three galaxies with actively accreting supermassive black holes in the early Universe during a period dubbed 'Cosmic Dawn' (< 1 Gyr after the Big Bang). At this time the most massive galaxies in the universe are believed to be having their growth spurt. Here we observe the shadows of molecular gas clumps ejected from the host galaxies and compare the outflows observed in our active galaxies with similar galaxies in the early universe that do not have accreting black holes. We find that although our sample consists of active galaxies that form stars at similar rates to the non-active galaxies, their outflows are less massive and less energetic. We suggest this is because the accreting black holes in our sample are all unobscured, meaning that the energy released by the black hole can freely escape the host galaxy and does not contribute to the ejection of gas. This unobscured phase follows an obscured phase where we believe outflows may be more extreme than even the star-forming galaxies.
- **Chapter 4**
  Similar to Chapter 3, we study a sample of five active galaxies with accreting supermassive black holes but at a later period in cosmic time called 'Cosmic Noon' ($\sim 2-4$ Gyr after the Big Bang). At this time the whole Universe is experiencing a growth spurt, forming more stars and accreting more material onto its black holes than at any other time in history. We target the diffuse neutral gas surrounding the host galaxies, as we did in Chapter 2 and compare the outflows in our sample with similar star-forming galaxies in the same cosmic period. We do not see any differences in the global outflow signatures between the two types of galaxies and instead associate such outflows with extreme galaxies in general (highly star-forming or active).
- **Chapter 5**
  In the last chapter, we present a large sample of mostly star-forming galaxies at Cosmic Noon. Using very sensitive and high-resolution images of the diffuse neutral gas surrounding these galaxies we are able to disentangle the outflowing gas from the gas standing still or flowing into the host galaxies. This is something that has so far not been possible to do in the diffuse neutral medium in a sample of galaxies at Cosmic Noon. We find that once the separate components are disentangled that trends can be found. Faster outflows appear to have more turbulent gas than slower outflows whilst the stationary gas is more likely to be turbulent in galaxies with more of the stationary gas.