Lyα Emission and Gaseous Outflows in a z∼2 Lensed Galaxy

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Introduction

Lyman α (Lyα) radiation is emitted by neutral Hydrogen gas when its electron cascades from the first energy level to the ground state. Many processes can cause or affect Lyα radiation, such as an incident Lyα light ray which is scattered, another, more energetic light ray, or the recombination of ionized Hydrogen and an electron. Since Hydrogen is so abundant, this means Lyα is among the most common emission features in the observable universe. Further, it also frequently interacts and rescatters in its environment due to this abundance, meaning an enormous amount of physical information about the radiation source and its surroundings is contained within the observed radiation (see § Expanding Shell Model).

Lyα radiation is also an excellent probe for a long-standing question: what reionized the universe? In its earliest days, the universe was so dense and hot that neutral Hydrogen could not exist. As it cooled, protons and electrons began to recombine to form neutral Hydrogen. A poorly understood process reionized much of this neutral Hydrogen. The radiation which is capable of ionizing Hydrogen is known as the Lyman continuum (LyC), but in the local universe, we do not observe it escaping from galaxies in sufficiently large quantities to explain this reionization process. During recombination, there is $\sim$2/3 chance for Lyα emission, so we expect Lyα radiation to track the amount of available protons and electrons for recombination (i.e. the fraction of Hydrogen ionized).

Expanding Shell Model

Current Lyα radiative transfer models of extragalactic sources [1] have often relied upon a simple picture in building theories of how Lyα is transmitted through space, known loosely as an expanding shell model. In this conceptualization, a source of Lyα radiation is situated at the center of a shell of neutral Hydrogen gas, expanding outward. Considering its simplicity, its broad success is peculiar, especially since it is known that extragalactic gas clouds have nonsymmetric, nonuniform geometries. However, recent suggestions hint that the effect of sufficiently globular morphologies converges to the same predictions as a spherical model [2].

The particular appearance of the radiation which makes its way to an outside observer tells a story of how the light scattered on its way. Many factors can affect this observation, but broadly speaking, its general shape is well explained by the properties (size, morphology, expansion velocity, optical depth, etc.) of the enveloping shell (a few examples are outlined in Figure 1).

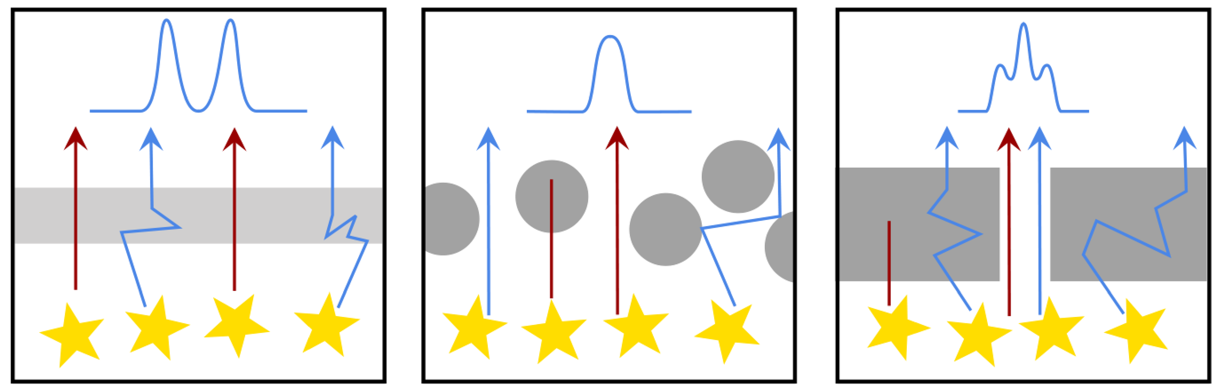

Figure 1: Three simple physical scenarios which lead to three different Lyα velocity profiles (pictured at top). From left to right: a completely covering neutral blanket, a globular neutral medium, and a neutral, optically thick shell with columns of low optical depth. Red lines are LyC and blue lines are Lyα. Image credit: [3].

Space itself is expanding, so most light sources seem to recede from us along our line-of-sight, causing the wavelength of light to stretch. This recession velocity is described by the cosmological redshift, z, measured by detecting the difference between the wavelength light is emitted at and its observed wavelength when it reaches Earth. For a galaxy with some redshift, we can also measure peculiar velocities, which are velocities in the galaxy's rest frame.

A Strongly Lensed Galaxy

Gravitational lensing is an effect predicted by the general theory of relativity, though initially Einstein and contemporaries believed the effect would be unobservable [4]. In the most simple case, a massive object lies between an observer and a light source. Light rays emitted by the source appear to be bowed due to the object's distortion of local spacetime curvature. When the source is aligned behind this gravitational lens, its image appears to be highly magnified.

Most commonly, an ultramassive galaxy cluster in the foreground acts as the lensing source of a background. Rather than a complete halo, the lensed images of the galaxy typically appear as thin, intermittent arcs roughly centered on the galaxy cluster.

Galaxy PSZ1-ARC G311.6602-18.4624 (hereafter referred to as the 'Sunburst Arc') is a strongly gravitationally lensed galaxy at $z = 2.37$, and is one of the brightest known lensed galaxies [3]. In the foreground lies a supermassive galaxy cluster which causes the lensing effect. Due to the lensing's magnification and distortion of the source image, the Sunburst Arc is unusually bright compared to nonlensed galaxies of similar age. The smearing effect also greatly aids in spatial resolution of different structures and features at fine scales, since the angular width of the arc on the sky is much greater than the source galaxy might normally appear.

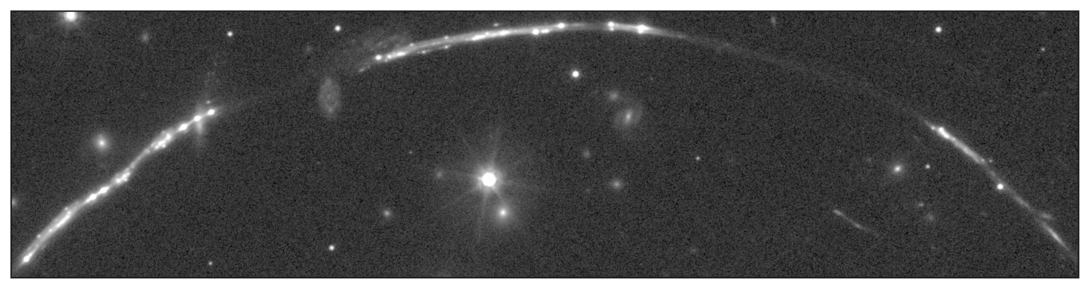

Figure 2: Direct HST imaging in the WFC3/UVIS F606W filter (sensitive to light at wavelengths similar to what the human eye can see) of the arc, showing three of four of the arcs which the galaxy appears as. A smaller fourth arc, unpictured, appears as a counterarc roughly opposite from the radius of curvature shown.

The Sunburst Arc is a confirmed LyC leaker, which distinguishes it in the cohort of $z \sim 2$ galaxies. This is of special interest because it could be more representative of gas morphologies which were more common in the earlier universe, and which led to reionization.

Results

Eight different locations on the two largest arcs were observed using the Magellan Echelette (MagE) spectrograph on the Magellan Baade telescope with exposure times between two and four hours, which collected light between the near-ultraviolet and near-infrared wavelengths with a median spectral resolution of $R \sim 5000$. A slit plate on the instrument blocks light apart from a small slit ($\sim 1'$ in length) on the sky [5], which permits the observation of discrete knots of the arc. The projections of these slit openings on the sky are shown in Figure 3.

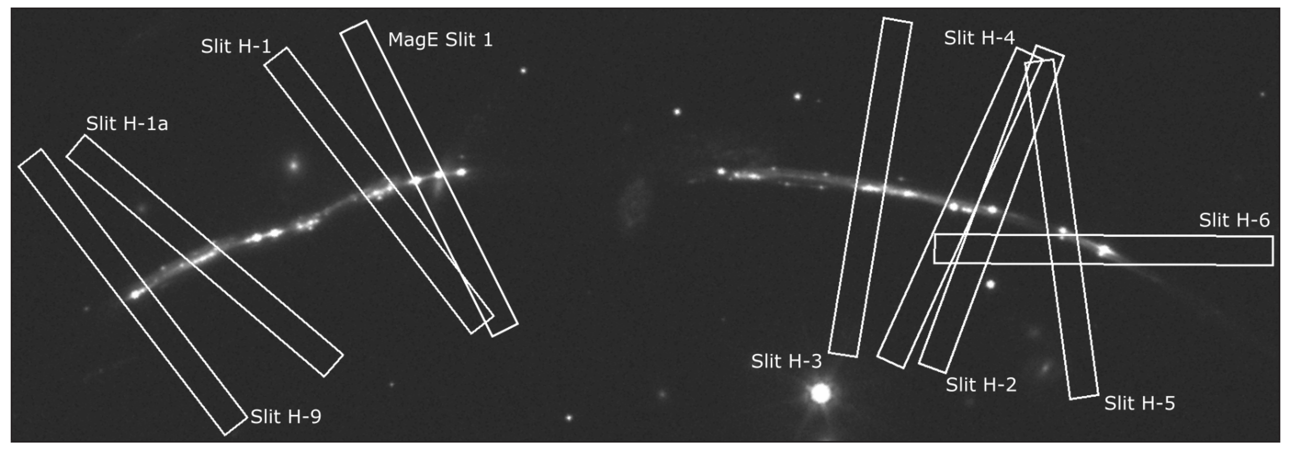

Figure 3: Spectroscopically sampled knots of the two main arcs. Boxes indicate the collection area on the sky.

At the galaxy's redshift, the rest-frame ultraviolet Lyα line appears in the bluest portion of optical light within the collected spectra. Measurements of the Hα, Hβ, and [OIII] emission lines were used to calculate the redshift [3]. Knowing the redshift, we use this to transform the spectra from wavelength space into the peculiar velocity space, which contains more significant physical information. In the galaxy's rest frame velocity, we can identify the Lyα emission structure within the galaxy itself since the peculiar velocities signify the velocity of the flux's emitting structure relative to the galactic center.

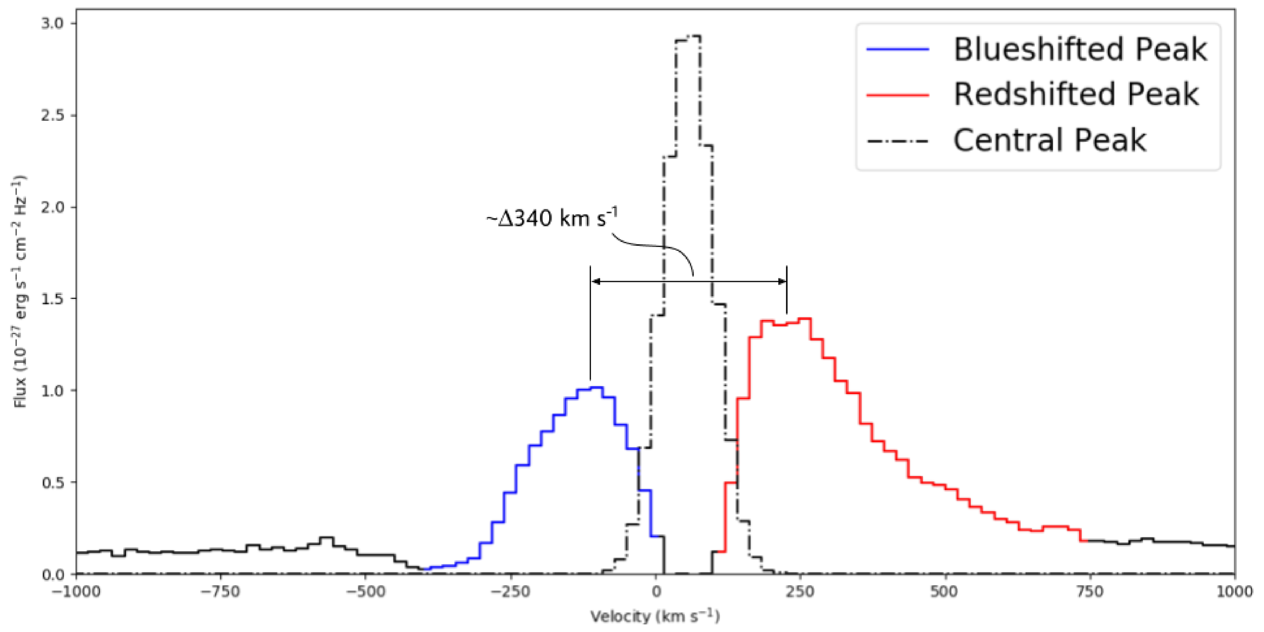

Figure 4: The velocity profile of slit H9 decomposed into three separate structures. The central peak shown in Figure 4 is approximated as a Gaussian distribution (labeled 'Central Peak'), which is subtracted from the overall profile, leaving two distinct peaks: a redshifted and blueshifted one. Notice the distinct velocity difference between the two peaks.

After performing this operation (shown for each spectrum in Figure 5), we see the dominant profile is a distinct triple-peak. To my knowledge, there is no other source with an observed Lyα profile similar to this. To understand this rarity, the profile is best split into three parts: a central peak, a blueshifted peak, and a redshifted peak (done for a single slit in Figure 4). The central peak represents Lyα flux which escapes from the galaxy unhampered, likely through the 'lanes' shown in Figure 1. The blueshifted and redshifted peaks represent Lyα emission which has been emitted by the central source and then scattered toward our line-of-sight by the close (blueshifted) or far (redshifted) side of the enveloping Hydrogen bubble. Distinct among the profiles is their obvious spatial variation along the length of the arc, such as the separation between the three peaks, their relative strengths, and their position in velocity space.

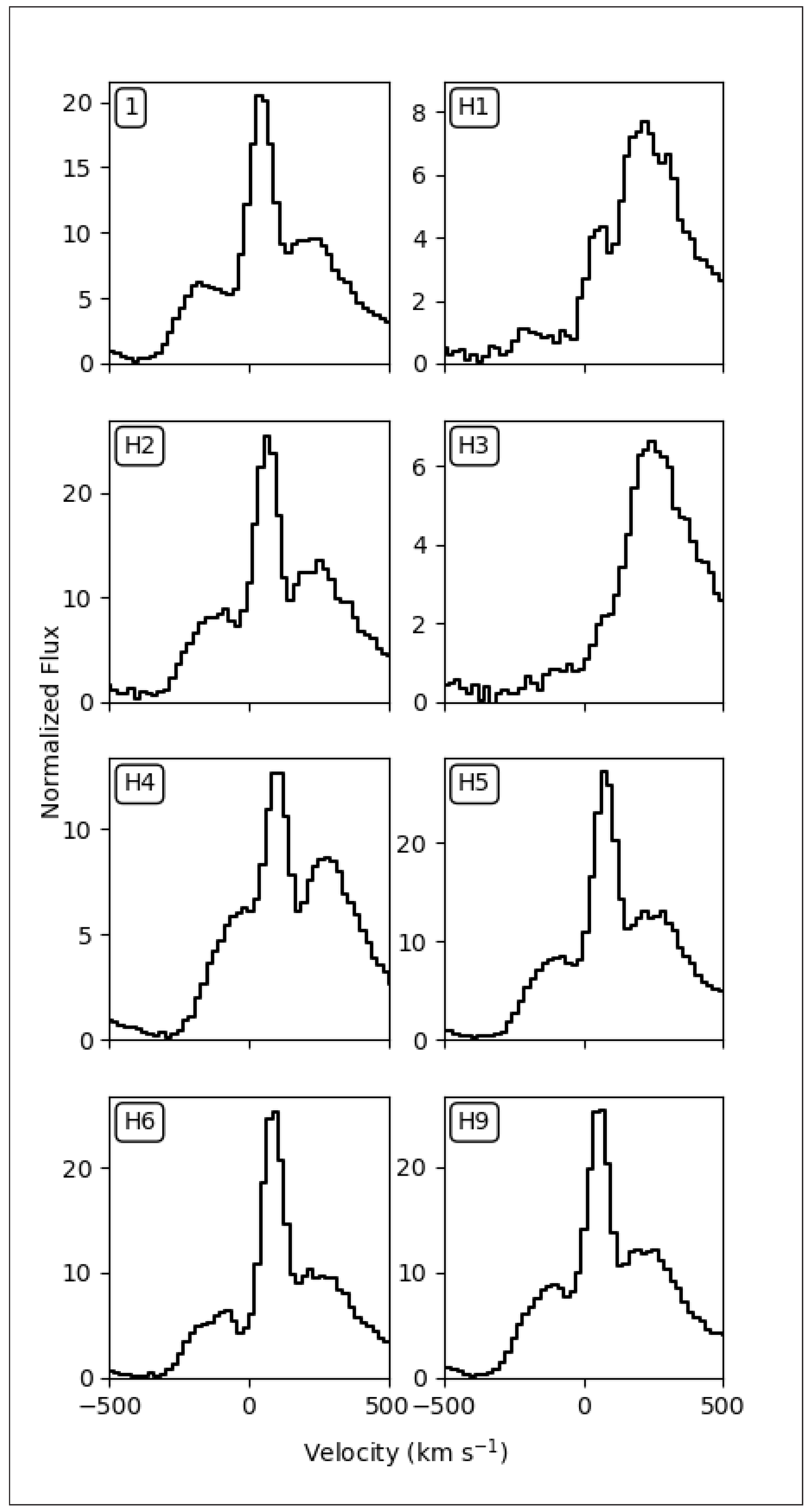

Figure 5: Velocity profiles of Lyα flux in the galaxy's rest frame, labeled by the slit number shown in Figure 3. The triple peak structure described in Figure 1 is evident in most samples, and they show strong spatial variation across the arc. The flux is normalized by dividing by the median flux of each spectrum.

References and Contact Information

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Future Research

We have presented a near-ultraviolet to near-infrared spectroscopic survey of the strongly lensed Sunburst Arc galaxy and discussed the spatial variation of its Lyα emission characteristics. The ultimate goal of this project is in the spirit of a higher-redshift analog of [6]. An immediate goal is to isolate and model the red and blueshifted peaks in the many triple peak structures. Further, absorption line analysis could lead to a better understanding of the roles of stellar winds and the interstellar medium in absorption and attenuation of the galaxy's light.

Recent higher-redshift studies have led to physical constraints on properties of ionized gas bubbles, based upon observed Lyα emission [7]. Mason & Gronke explicitly suggest a deep spectroscopic survey across a spatially distinct area could allow a direct mapping of an ionized bubble. The spectra presented could be the start to such an endeavor and have implications in a lower-redshift test of their model and understanding Lyα escape conditions and its relation to the LyC and reionization.