Star Formation in High Redshift Galaxies

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Abstract. Observations of the high redshift Universe, interpreted in the context of a new generation of computer simulated model Universes, are providing new insights into the processes by which galaxies and quasars form and evolve, as well as the relationship between the formation of virialized, star-forming systems and the evolution of the intergalactic medium. We describe our recent measurements of the star-formation rates, stellar populations, and structure of galaxies and protogalactic fragments at $z \sim 2.5$, including narrow-band imaging in the near-IR, IR spectroscopy, and deep imaging from the ground and from space, using HST and ISO.

1. Introduction

Observations of the Hubble Deep Field, and other surveys of high redshift galaxies described in these proceedings, are contributing to a new picture of how large galaxies such as the Milky Way were assembled. One interpretation of the data so far is that large galaxies collapse out of what appears as several star-forming proto-galactic fragments at $z \sim 2 – 3$ (Pascarelle et al. 1996; Haehnelt, Steinmetz & Rauch 1998). Here we describe our search for Hα emission from the star-forming regions in high redshift galaxies, which is redshifted into the near-infrared. We focus on one of the outstanding questions about these objects: is the burst of star-formation seen in the UV continuum producing the dominant
stellar population (by mass)? We show that for most high redshift objects, the data available to date provide only weak constraints on the age of the dominant stellar population (see also the discussion by Sawicki & Yee 1998). An exception is our observation of the observed mid-IR (rest-frame near-IR) continuum of the \( z = 2.7 \) galaxy MS1512-cB58 using ISOCAM. For this object, we can put a strong limit on the fraction of the mass comprised of an old population of stars.

2. The \( z = 2.515 \) gravitational arc of Abell 2218

To illustrate the ambiguity in the age of the dominant stellar population, in this section we describe observations of the \( z = 2.515 \) galaxy which is lensed by Abell 2218. Abell 2218 is a rich cluster of galaxies at \( z = 0.171 \) (Abell et al. 1989; Kristian et al. 1978). It was one of the first to be observed to have arcs caused by the lensing of background galaxies (Lynds & Petrosian 1986; Pello-Descayre et al. 1988), and has been the subject of many studies. Of particular interest is the discovery by Ebbels and collaborators (E96) that one of the brightest blue arcs is a star-forming galaxy at \( z = 2.515 \) (Arc A, or galaxy #384). The appearance of the optical spectrum of the arc, as well as the optical/IR spectral energy distribution, imply that Arc A is typical of the star-forming galaxies discovered by Lyman dropout techniques (Steidel et al. 1996a) or in the Hubble Deep Field (Williams et al. 1996, Lowenthal et al. 1997, Cohen et al 1996, Steidel et al. 1996b), except that its apparent magnitude is boosted by about a factor of 14.5 by lensing (Saranti, Petrosian & Lynds 1996). Arc A is similar in apparent properties to MS1512-cB58, described below.

We obtained a narrow-band image of \( \text{H} \alpha \) emission from A2218’s Arc A using the IRTF NSFCAM and tunable narrow-band filter, or CVF (\( R \approx 90 \), Figure 1). Further details are provided in Bechtold & Elston (1998, in preparation). For Arc A, the excess emission in the CVF image compared to the \( K' \) image implies a rest-frame equivalent width of \( \sim 85 \, \text{A} \) and a narrow band flux of \( 7.35 \times 10^{-16} \, \text{ergs cm}^{-2} \, \text{sec}^{-1} \). For \( z = 2.515 \), this corresponds to a luminosity in the excess narrow-band emission of \( 3.25 \times 10^{43} \, h_{75}^{-2} \, \text{ergs sec}^{-1} \) for \( q_0 = 0.1 \). The observed \( \text{H} \alpha \) luminosity implies a total observed star-formation rate (SFR) of \( 290 \, h_{75}^{-2} \, \text{M}_\odot \, \text{yr}^{-1} \) if we adopt the calibration of Kennicutt (1983), that is, SFR (\( \text{M}_\odot \, \text{yr}^{-1} \)) = L(\( \text{H} \alpha \))/1.12\times10^{41} \, \text{ergs s}^{-1} \). For \( q_0=0.5 \), SFR = 135 \( h_{75}^{-2} \, \text{M}_\odot \, \text{yr}^{-1} \). This assumes an IMF consistent with Salpeter (1955), an upper mass cut-off of 100 \( \text{M}_\odot \), and 1.1 magnitudes of extinction at \( \text{H} \alpha \). This value for the extinction is consistent with the reddening derived from the spectral energy distribution (Figure 2).

If we assume that the galaxy seen as Arc A is magnified by lensing by a factor of 14.5, then the star-formation rate for Arc A is 20 \( \text{M}_\odot \, \text{yr}^{-1} \) for \( q_0=0.1 \), and 9.3 \( \text{M}_\odot \, \text{yr}^{-1} \) for \( q_0=0.5 \). This is very typical of the star-formation rates estimated from the UV continuum luminosity for Lyman dropout galaxies or Hubble Deep Field galaxies (Madau et al 1996; Steidel et al. 1996a).

Moreover, Arc A in the CVF image appears bright on its eastern edge compared to the \( K' \) image. The seeing for the IRTF data was about 0.4 ″, compared to a total linear extent of about 5 ″ for the arc, so it is well-resolved spatially. We also show the WFPC2 image of A2218 through the F702W filter from the HST archive (the WFPC2 data was presented by Kneib et al. 1996).
Figure 1. Contour plots of Hα image of Arc A (#384) and Arc #362 (left) at the same scale and orientation as the WFPC-2 image (right). North is up and east is to the left; 30′′ × 30′′ is shown. Arc A and the optically faint Arc #362, both appear to have excess emission in the narrow band image compared to the K image. Arc #362 appears to be as blue as Arc A, compared to the numerous arcs at lower redshift which are red (e.g. plate 1 of Saraniti, Petrosian & Lynds 1996). Thus Arc #362 is probably a counterimage of Arc A, at z ≈ 2.515. Another spectroscopically confirmed counter-image of Arc A, #468 (E96) was not in our field of view.

The bulk of the excess emission appears to be concentrated in a region along the arc which is fairly faint in the F702W stellar continuum (rest frame λ2000Å). Thus the effect of the lensing is to stretch out what is probably a small, compact galaxy and allow us to see that star-formation is not happening in a single, co-eval and co-spatial burst.

We refit the broad-band spectral energy distribution (SED) of Arc A, which was discussed by E96. The theoretical curves shown by E96 did not fit the SED very well, and new models have subsequently become available (Leitherer et al. 1996 and references therein). We tried several models, chosen to span the important parameters, and found a few good fits to the SED: see Figure 2. Instantaneous single burst models, e.g. those of Bruzual & Charlot (1996, denoted GISSELL in the figures) or Fioc & Rocca-Volmerange (1997, denoted RVF in the figures), fit better than continuous star-formation models, and an age of 40 Myrs gives the best fit, with E(B-V)=0.18, assuming an LMC-like reddening law. However, this model predicts a very small equivalent width for Hα emission, W(Hα)≈ 0.1 Å (Leitherer & Heckman 1995), in clear conflict with the observations. For the reddening law for starbursts given by Calzetti (1997),
which one expects to be more appropriate, the fit is somewhat worse, and the age derived quite different: 3.8 Myrs, and E(B-V)=0.35 gives the best fit, and the predicted W(Hα) \sim 100\AA, in better agreement with the Hα observation.

Thus the large reddening correction needed in the UV makes conclusions regarding the age and star-formation rate of Arc A uncertain. Moreover, the data points shown in Figure 2 are for the broad band fluxes integrated over the entire galaxy. The Hα picture indicates already that the star-formation is not coeval over the whole galaxy. An alternative possibility is that star-formation has been episodic. In Figure 2 we show a second model, where we fit two bursts, one fixed at an age of 2 Gyr (with LMC reddening; the age of the Universe at z \approx 2.5 is not much older than 2 Gyrs) and a 5 Myr old burst (and Calzetti reddening). This two burst model fits the data very well, and the older burst contains >95 percent of the mass of the galaxy. This is qualitatively a very different star-formation history for this galaxy than the single burst model, one which the current data cannot rule out.

An older population could be detected by rest-frame near-IR photometry, but for z \sim 2-3, the rest-frame near-IR is redshifted into the mid-IR, and is beyond the sensitivity of current instruments for most objects. In the next section, we describe ISOCAM observations of MS1512-cB58, at z = 2.7, which we obtained in order to limit the presence of an older stellar population.

3. Mid-IR ISOCAM observations of MS1512-cB58

MS 1512-cB58 is a galaxy which was discovered serendipitiously (Yee et al. 1996) during the course of the CNOC-1 redshift survey of moderate redshift galaxy clusters (Yee, Ellingson & Carlberg 1996). It is at z = 2.7 with apparent
V = 20.5. Its observed optical (rest-frame UV) spectrum resembles that of local starburst galaxies (Yee et al. 1996, Steidel et al. 1996a; see also Conti, Leitherer & Vacca 1996). The lack of a 4000 Å break in the rest frame (Ellingson et al. 1996) conveniently redshifted so that the broad-band J and H filters straddle it, implies a very young age, as does the appearance of the C IV λ1550 P-Cygni profile caused by winds associated with the hot stars. The best fit to the SED is a continuous star-formation model of about 10-20 Myr, with LMC reddening of $E(B-V) \sim 0.3$. Bechtold et al. (1997) detected Hα emission, confirming a high star-formation rate for MS 1512-cB58. However, as in the case of the A2218 arc, the limits on the presence of an older stellar population are weak. Ellingson et al. (1996) showed that if a two burst model is fit to the spectral energy distribution, an older, 2 Gyr old burst could comprise as much as 85% of the galaxy mass.

MS1512-cB58 has the brightest apparent magnitude of the high redshift star-forming galaxies discovered so far, which is in part a result of the relatively young age of its starburst, and in part because of magnification by gravitational lensing by a foreground $z = 0.37$ cluster of galaxies (Seitz et al. 1998, Ellingson et al. 1998). The magnification factor is probably as high as 25×. Thus, MS1512-cB58 is an ideal candidate for mid-IR observations.

We used the long wavelength camera of the CAM instrument (Cesarsky et al. 1996) aboard the Infrared Space Observatory (ISO, Kessler et al. 1996) to image MS1512-cB58 through two broad band filters, LW2 (centered on 6.7 μm) and LW10 (centered on 11.5 μm), covering rest-frame 1-4 μm for MS1512-cB58. Details of the observations and data reduction are given in Bechtold, Yee & Ellingson (1998, in preparation). The data were spatially oversampled in order to resolve MS1512-cB58 from the central cD galaxy of the foreground cluster, which lies only 6 ″ away. The noise in deep ISOCAM images is primarily from unresolved point sources, and so we evaluated the significance of all sources from the variation from point to point in the images themselves. We require sources to be detected at >3σ in both filters, with the result that MS1512-cB58, the central cD and several other members of the foreground cluster are detected.

The spectral energy distribution for MS1512-cB58, including the ISOCAM flux points, is shown in Figure 3. The ISOCAM flux points fall on the extrapolation of the young burst model which best fits the optical and near-IR data points, with very little room for the addition of an older population. Less than 10% of the mass of MS1512-cB58 can be in a 2 Gyr population. Thus, MS1512-cB58 may well be a true proto-galaxy, undergoing its very first burst of star-formation. Further mid-IR observations of MS1512-cB58 and other high redshift galaxies will be possible with SIRTF and NGST.

4. Hα from Damped Lyα absorbers

For many years, quasar absorption lines have been used to study the evolution of galaxies and the intergalactic medium at high redshift. The damped Lyα systems in particular are generally thought to be the progenitors of present-day galaxies (Wolfe et al. 1986) and should thus be signposts for distant normal galaxies in an early stage of evolution. Prochaska & Wolfe (1996, 1997) have suggested that the asymmetric line profiles seen in the metal lines associated with
damped systems support the view that damped Ly-α systems are large rotating disks. On the other hand, Haehnelt, Steinmetz & Rauch (1998) suggest that such profiles can occur naturally in systems composed of smaller protogalactic fragments. Direct detection of the galaxies causing damped Lyman-α absorbers will help interpret the large body of spectroscopic observations of them in the context of the formation of galaxies and structure. Deep imaging of the fields of damped Lyman-α systems does appear to show a statistical excess of luminous galaxies near the quasar line of sight (e.g. Aragon-Salamanca, Ellis & O’Brien 1996). But without redshifts, one cannot actually associate any particular galaxy with a given absorption line system.

We have used the IRTF NSFCAM and Palomar 5m Near-IR CASS camera to search for Hα redshifted into the K band, associated with damped Lyα quasar absorption line systems. Details of the observations are given in Elston, Bechtold & Cutri (1998, in preparation). We obtain images through a 1% narrow band filter (CVF) tuned to Hα at the redshift of the damped Lyα absorbers. So far, this technique has proven very powerful: we have detected Hα companions for most of the systems observed, with separation of between 2 and 12 arcsec from the quasar line-of-sight. Often, multiple faint, very compact objects are found in a single field. We interpret these Hα emitters to be clumps of star-forming gas in the same sheet or filament which contains the damped Lyα absorber.

We are in the process of confirming these with slit spectra at the KPNO 4m with CRSP, and UKIRT. Using the standard conversion between Hα flux and star-formation rate our typical 3σ sensitivity is about 5 M⊙ yr⁻¹. If the Hα fluxes are attributed to photo-ionization by young stars it appears that star formation rates of 10-20M⊙ yr⁻¹ are pervasive at redshifts of 2.5 in agreement with the Lyman-dropout population found by Steidel et al. (1996) suggesting they are similar populations.
Figure 4. Volume-averaged star formation rate ($M_\odot$ yr$^{-1}$ Mpc$^{-3}$) as a function of redshift. Open symbols are derived from UV luminosity, filled symbols from H$\alpha$. Open circles, Lilly et al. 1996; Open squares, Madau et al. 1996 (HDF); Filled Triangle, Gallego et al. 1996; Filled Circle, Tresse & Maddox, 1997; Filled square, our work.

If these observations of individual systems are representative, we can combine the star-formation rates with the statistics of the incidence of damped Ly$\alpha$ absorbers in quasar lines-of-sight (Wolfe et al. 1995), to make a preliminary estimate of the volume-averaged star-formation rate (Pei & Fall 1995; Fall, Charlot, & Pei 1996; Madau et al. 1996) at $z \sim 2.5$ (not all candidates have been spectroscopically confirmed yet). Figure 4 shows the result. Our results are consistent, within large uncertainties, with the results derived from the UV continuum luminosity by Madau et al. (1996). However, our data so far suggest that the peak in star-formation may have taken place at somewhat higher redshift than indicated by the Madau et al. analysis. Combining our data with observations of the H$\alpha$ luminosity of low and moderate redshift galaxies will allow an important check on the star-formation rates in the Universe derived from other means.

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