Astro-Imaging at Blue Mountain

Dick Steinberg

DVAA Meeting

December 17, 2010

Astro-Imaging at Blue Mountain

- **Site, telescopes and cameras**
- **Wide-field color (106mm Takahashi FSQ + SSPro)**
  - The moon (~1 L s or $4x10^{-14}$ Mly)
  - Milky Way nebulae and clusters (~10^{-3} Mly)
  - Nearby galaxies (~10 Mly)
- **Deep monochrome (317mm Hyperion + U16M)**
  - Strongly-lensed galaxy (z=0.38 & 2.73 → 4.3 & 12 Gly)
  - Quadruply-imaged quasar (z~3)

Blue Mountain Vista Observatory

On the Colosimo property in New Ringgold PA

Initial Installation at BMVO, Jan 2010

Thanks to Don D'Egidio and Frank Colosimo

Initial Installation at BMVO, Jan 2010

Don and Dick

The Telescopes

- Takahashi FSQ-106N quadruplet fluorite APO refractor 106mm f/5

- Starizona Hyperion corrected Cassegrain reflector 317mm f/8

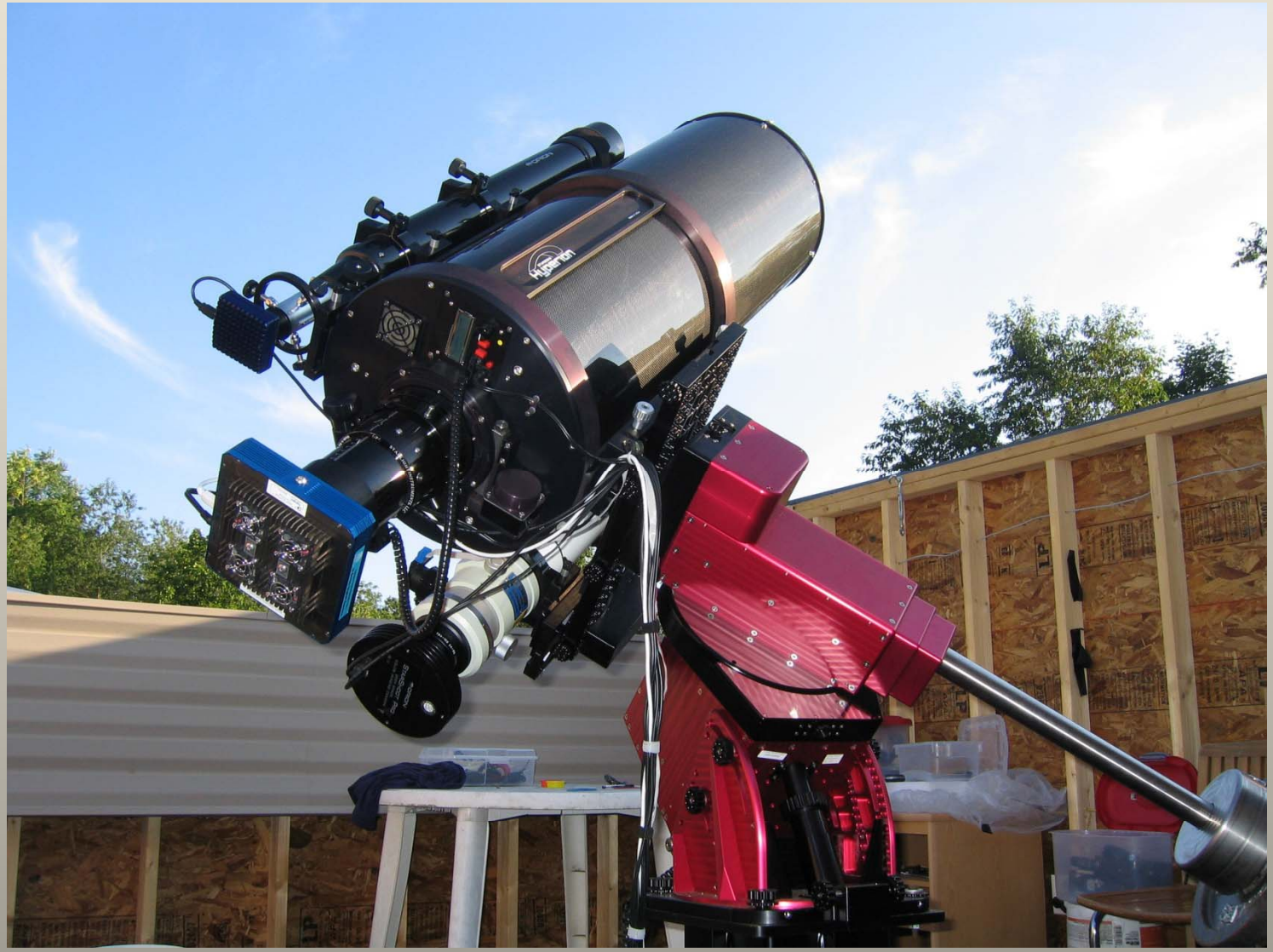
  70 mm image circle

Hyperion 12.5” f/8 Corrected Cassegrain

on AP1200 mount in Narberth PA, May 2010

3 scopes, 3 cameras 1 mount

on Paramount ME at BMVO, New Ringgold, PA - July 2010



The Cameras

- Color – Orion StarShoot Pro v1

  (used with NP101 and TAK FSQ106)

- Monochrome – Apogee U16M

  (used with 12.5" Hyperion)

Orion StarShoot Pro v1

- One-shot color camera, Bayer filter matrix
- 3032x2016 pixels (total 6.1 MP), each 7.8 x 7.8 microns
- Chip size 25.1x17.6 mm
- Unregulated thermoelectric cooling
- FOV w FSQ106 – 2.5 x 1.7 degrees
- Plate scale – 3.01 arc sec/pixel
- Used for wide-field color images
- Limiting magnitude ~16

Apogee U16M

- Large chip monochrome camera
- Kodak KAF-16801E full frame CCD
- 4096x4096 pixels (16MP total), each 9 x 9 microns
- Chip size 37x37 mm (52mm diagonal)
- FOV with 12.5" Hyperion – 50x50 arc min
- Plate scale – 0.73 arc sec/pixel
- Microlenses and anti-blooming gates
- Peak QE (550nm) 69%
- Thermoelectric cooling (max 45 C below ambient)
- Limiting magnitude ~21 (w 12.5" Hyperion at BMVO)

Two-day old Moon

M8, the Lagoon Nebula in Sagittarius

M20, the Trifid Nebula in Sagittarius

The California Nebula in Perseus, NGC1499

The Pleiades, M45

M42, the Orion Nebula

Barnard 33, the Horsehead Nebula in Orion

(part of IC434)

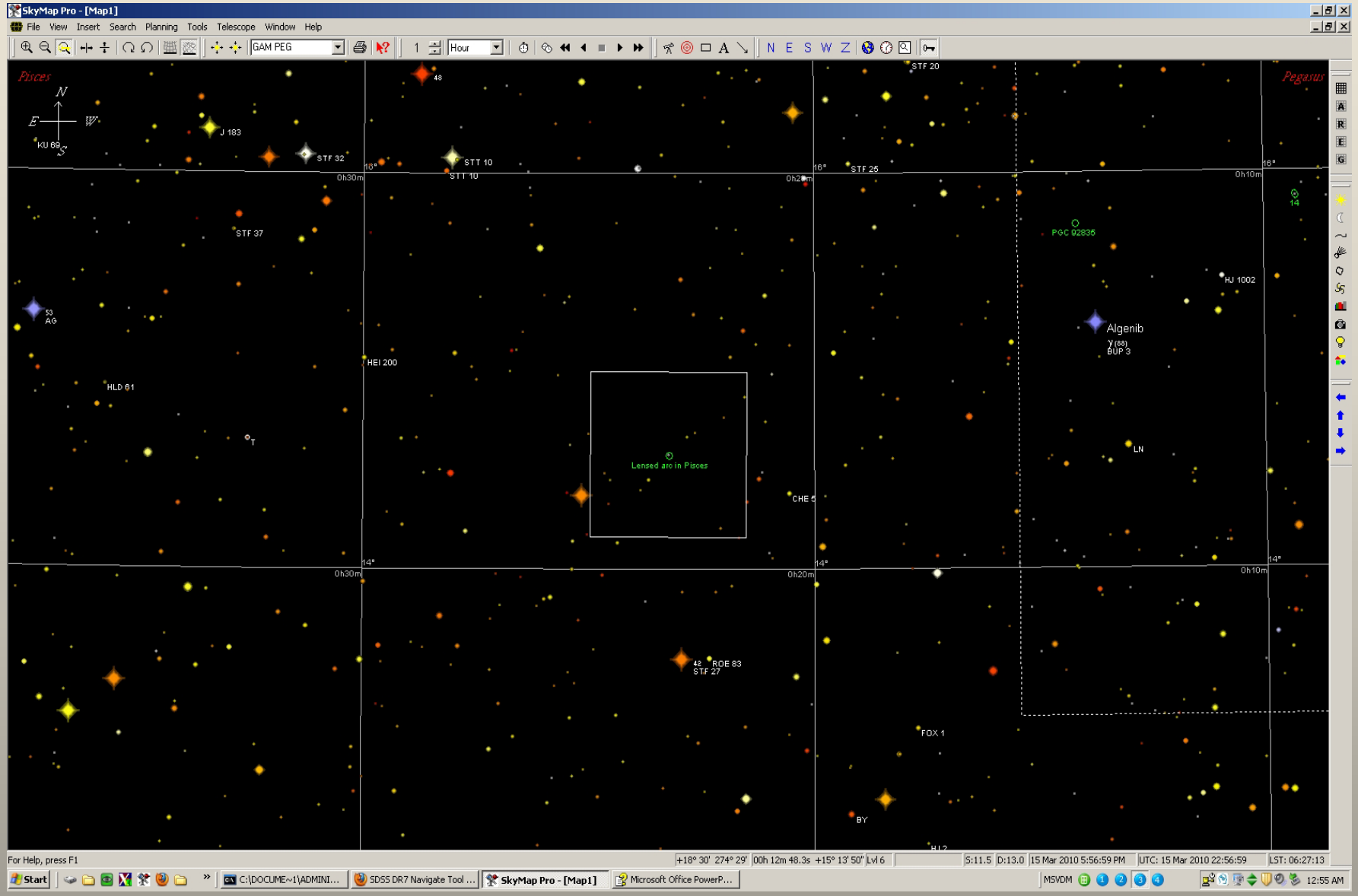
The Rosette Nebula in Monoceros

NGC 2237

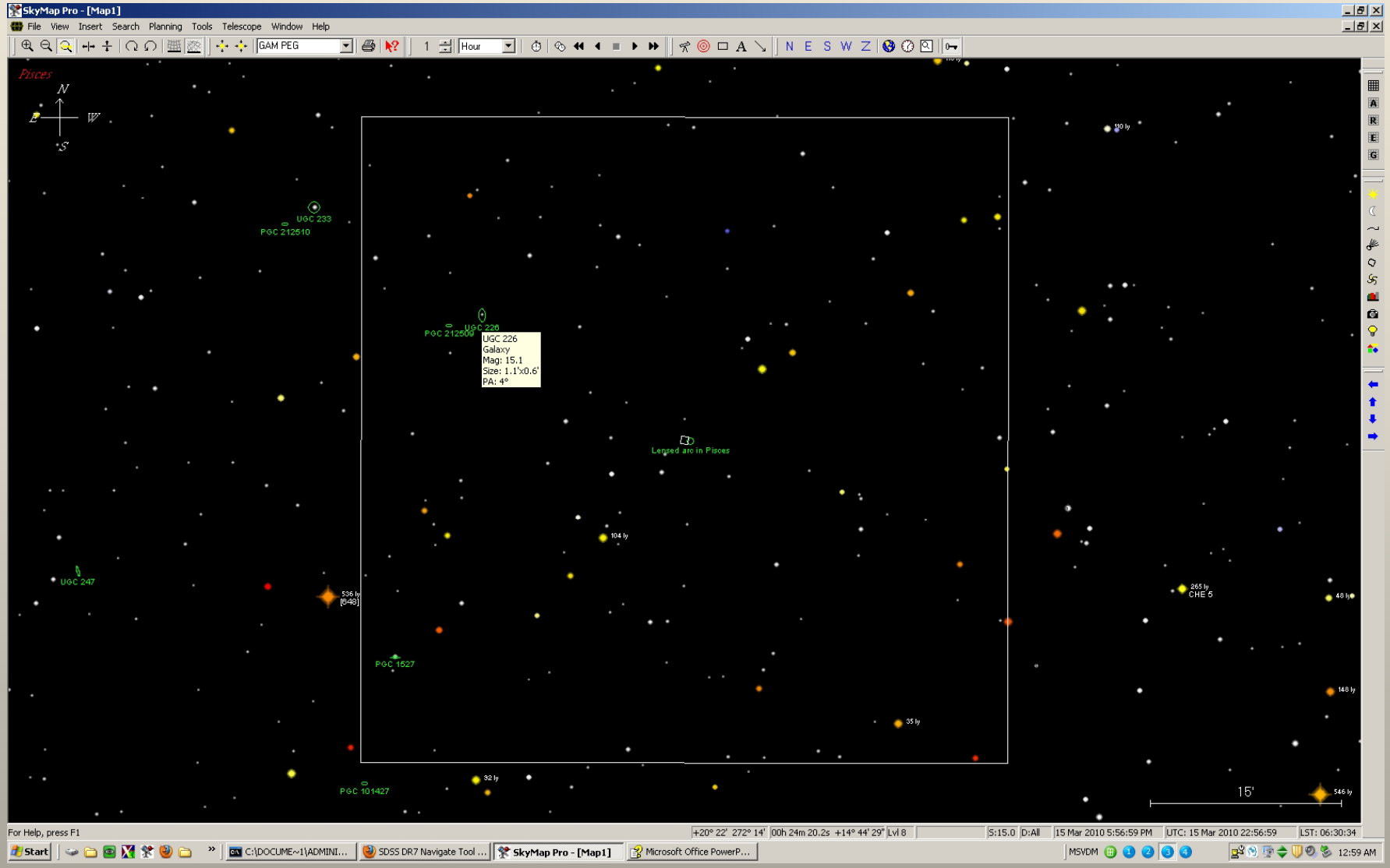
M31, the Andromeda Galaxy

M57, the Whirlpool Galaxy

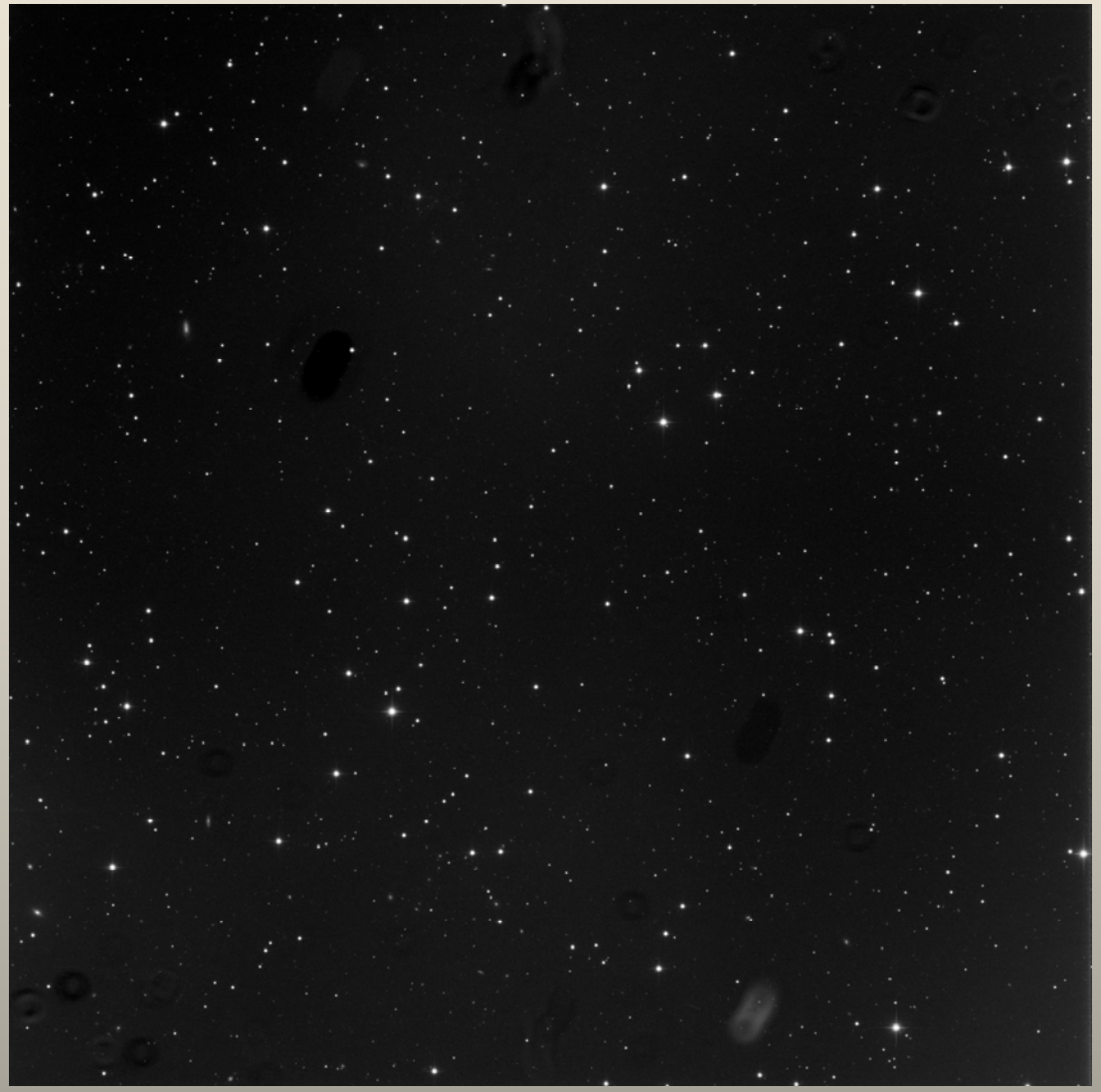
Lyman Break Galaxy (LBG) in Pisces



Lyman Break Galaxy (LBG) in Pisces



Lyman Break Galaxy (LBG) in Pisces



50 x 50 arc min near Algenib
(SE corner of the great square of Pegasus)

Lyman Break Galaxy (LBG) in Pisces

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THE 8 O'CLOCK ARC: A SERENDIPITOUS DISCOVERY OF A STRONGLY LENSED LYMAN BREAK GALAXY IN THE SDSS DR4 IMAGING DATA

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ABSTRACT

We report on the serendipitous discovery of the brightest Lyman Break Galaxy (LBG) currently known, a galaxy at $z = 2.73$ that is being strongly lensed by the $z = 0.38$ Luminous Red Galaxy (LRG) SDSS J002240.91+143110.4. The arc of this gravitational lens system, which we have dubbed the "8 o'clock arc" due to its time of discovery, was initially identified in the imaging data of the Sloan Digital Sky Survey Data Release 4 (SDSS DR4); followup observations on the Astrophysical Research Consortium (ARC) 3.5m telescope at Apache Point Observatory confirmed the lensing nature of this system and led to the identification of the arc's spectrum as that of an LBG. The arc has a spectrum and a redshift remarkably similar to those of the previous record-holder for brightest LBG (MS 1512-cB58, a.k.a "cB58"), but, with an estimated total magnitude of $(g,r,i) = (20.0,19.2,19.0)$ and surface brightness of $(\mu_g,\mu_r,\mu_i) = (23.3, 22.5, 22.3)$ mag arcsec^{-2}, the 8 o'clock arc is thrice as bright. The 8 o'clock arc, which consists of three lensed images of the LBG, is 162°(9.6″) long and has a length-to-width ratio of 6:1. A fourth image of the LBG — a counter-image — can also be identified in the ARC 3.5m g-band images. A simple lens model for the system assuming a singular isothermal ellipsoid potential yields an Einstein radius of $\theta_{\rm Ein} = 2.91'' \pm 0.14''$, a total mass for the lensing LRG (within the $10.6\pm0.5\ h^{-1}$ kpc enclosed by the lensed images) of $1.04\times10^{12}h^{-1}M_\odot$, and a magnification factor for the LBG of $12.3^{+15}_{-3.6}$. The LBG itself is intrinsically quite luminous ($\approx 6\times L_*$) and shows indications of massive recent star formation, perhaps as high as 160 $h^{-1}M_\odot$ yr^{-1}.

Subject headings: gravitational lensing — galaxies: high-redshift

1. INTRODUCTION

Strongly lensed galaxies are particularly useful for studies of galaxy evolution due to the magnification of the galaxy magnitude: since surface brightness is conserved by lensing, the stretching of the galaxy shape increases the apparent brightness of the source galaxy. These apparently brighter objects are then prime candidates for detailed follow-up studies at a fraction of the telescope time that would be necessary for comparable but unlensed galaxies.

If a strongly lensed galaxy also happens to be a Lyman Break Galaxy (LBG), so much the better. LBGs are galaxies in which the low-flux region of the spectrum blueward of the Lyα Hydrogen line at 1216Å has been redshifted into the U band; LBG samples thus provide a vital window into the galaxy populations of the high redshift ($z > 2.7$) Universe (e.g., Adelberger et al. 1998, 2003; Steidel et al. 1998; Giavalisco et al. 1998). LBGs, however, are generally rather faint, and detailed studies of these high-redshift galaxies profit from the additional magnification provided for by strong lensing (Nesvadba et al. 2006).

Previously, just two examples of strongly lensed LBGs have been discovered: MS1512-cB58 at $z = 2.7$ (a.k.a, "cB58"; Yee et al. 1996, Teplitz et al. 2000, Pettini et al. 2002, Baker et al. 2004) and the 1E0657-56 arc+core at $z = 3.2$ (Mehlert et al. 2001). A search by Bentz et al. (2003) using the Sloan Digital Sky Survey Early Data Release (SDSS EDR; Stoughton et al. 2002) yielded six bright ($r \sim 20$) candidate LBGs with $z = 2.45 - 2.80$, but these were later found to be unlensed bright quasars (Ivison et al. 2005).

Here, we report on the serendipitous discovery in the SDSS data of the brightest case of these rare objects, a strongly lensed $z = 2.73$ LBG which we have nicknamed the "8 o'clock arc".

This letter is organized as follows: § 2 describes the initial discovery in the SDSS imaging data, § 3 describes the confirmatory followup imaging and spectroscopy, and § 4 describes modeling and comparison with previously known high redshift LBGs. § 5 contains discussion and § 6 concludes. Throughout, we assume a flat cosmology with $\Omega_{\rm m} = 0.3$, $\Omega_\Lambda = 0.7$, and $H_0 = 100h$ km s^{-1} Mpc^{-1}, unless otherwise noted.

2. THE INITIAL DISCOVERY

The SDSS (York et al. 2000) is a digital imaging and spectroscopic survey that, over the course of five years, has mapped nearly one quarter of the celestial sphere in five filter bands ($ugriz$; Fukugita et al. 1996) down to $r = 22.2$ and has obtained spectra for $\approx 10^6$ astronomical objects (Adelman-McCarthy et al. 2007) . Although the SDSS completed its first phase of operations in June 2005, a three-year extension known as SDSS-II is in progress. (For more details on SDSS-II, please consult `www.sdss.org`.)

To explore the effects of interactions on the properties of galaxies in different environments, Allam et al. (2004) extracted a catalog of interacting/merging galaxy pairs from the SDSS imaging data. During visual inspection of a new version this catalog (Allam et al. 2007) based upon the SDSS DR4 (Adelman-McCarthy et al. 2006) imaging data, a very unusual merging galaxy pair with a galaxy-galaxy separation of 4.02″was discovered (see Fig. 1). The two components of this system are SDSS J002240.91+143110.4, which is a Luminous Red Galaxy (LRG), and SDSS J002240.78+143113.9, which is a very blue and elongated object. The SDSS targeted SDSS J002240.91+143110.4 (hereafter, "the LRG"; for LRG selection, cf. Eisenstein et al. 2001) with a 3″spectroscopic fiber. The resulting spectrum (Fig. 2) shows absorption features of an early type galaxy at redshift of z=0.38 with Ca H and K lines at 5463 and 5510Å. The very blue and elongated SDSS J002240.78+143113.9 was not targetted for SDSS spectroscopy and hence has no SDSS spectrum.

Allam recognized this system as a probable gravitational lens and, due to its time of discovery, dubbed it the "8 o'clock arc." The arc is a very blue high surface brightness object north of the LRG, subtending an angle of ≈162°about the galaxy.

The arc consists of three components, which are the blue A1 (SDSS J002240.78+143113.9) the reddish blue A2 (SDSS J002240.96+143113.9), and the blue A3 (SDSS J002241.14+143112.7). The arc containing these three components extends over 9.6″in length and has a length to width ratio of 6:1.

3. THE CONFIRMATION

In order to confirm the identification of the system as a gravitational lens, we carried out follow-up imaging and spectroscopy on the Astrophysical Research Consortium (ARC) 3.5m at Apache Point Observatory on the night of 2006 August 24 (UT).

3.1. *Imaging*

The imaging was obtained under photometric conditions and with a seeing of 1.0–1.2″ (FWHM) during the first half of the night. The instrument used was the SPIcam CCD imager, which has a field-of-view of 4.78′ × 4.78′. Three exposures of 300 sec each were obtained in each of the SDSS gri filters; a 15″ dithering pattern about the LRG was employed.

The resulting images were processed using the IRAF `ccdred` package. The images were then co-added with the `swarp` package (Bertin 2000, v2.16; see Fig. 3), and object detection and measurement were made with `SExtractor` (Bertin & Arnouts 1996). We used a weighted coaddition, accounting for flux scaling between the images, and aperture photometry with an aperture of 3″. Photometric zeropoints were derived by matching objects detected in the co-added images with objects in the SDSS imaging data and comparing their `SExtractor MAG_AUTO` instrumental magnitudes with their SDSS model magnitudes. The gri magnitudes measured from these co-added images are listed in Table 1. An astrometric solution for the coadded images was measured relative to the SDSS overlapping bright stars in the field of view.

3.2. *Spectroscopy*

Slit spectroscopy was carried out with the DIS III (Dual Imaging Spectrograph) using the standard Medium Red/Low Blue grating setup during the second half night of night. Six exposures were obtained under moon-less conditions for a total exposure time of 140 min. The seeing was 1″–1.2″ (FWHM). A slit width of 1.5″was employed, and the slit was oriented to cover as much of the three components of the 8 o'clock arc as was possible. The standard Medium Red/Low Blue grating setup covers an effective spectral range of 3600Å to 9600Å at a linear resolution of 2.43″pix^{-1} in the blue part

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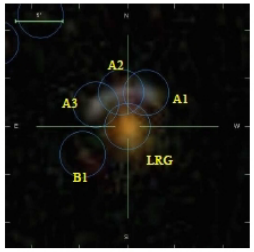


FIG. 1.— SDSS gri color image showing the location of three lensed images (A1, A2, A3), the position of the LRG, and a faint back ground LRG (B1) at photometric redshift of 0.53.

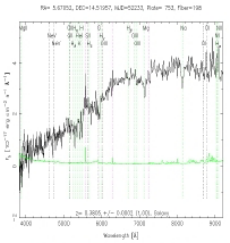


FIG. 2.— The SDSS spectrum for the LRG SDSS J002240.91+143110.4.

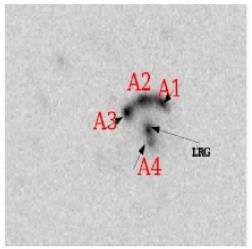
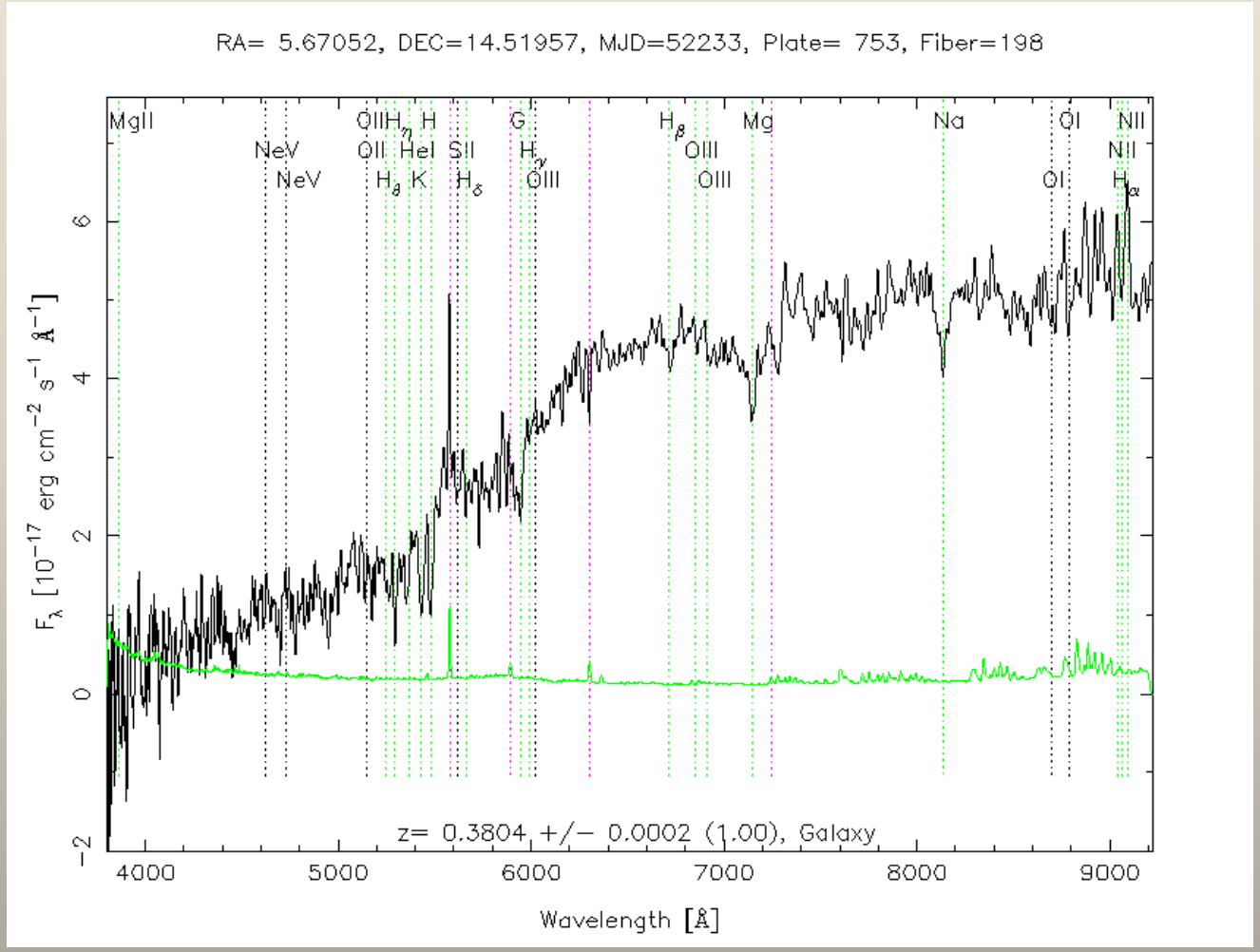


FIG. 3.— The coadded ARC 3.5m SPICAM g-band image clearly shows the three components of the arc (A1, A2, A3) as well as the counter image (A4); the center of the LRG is also marked.

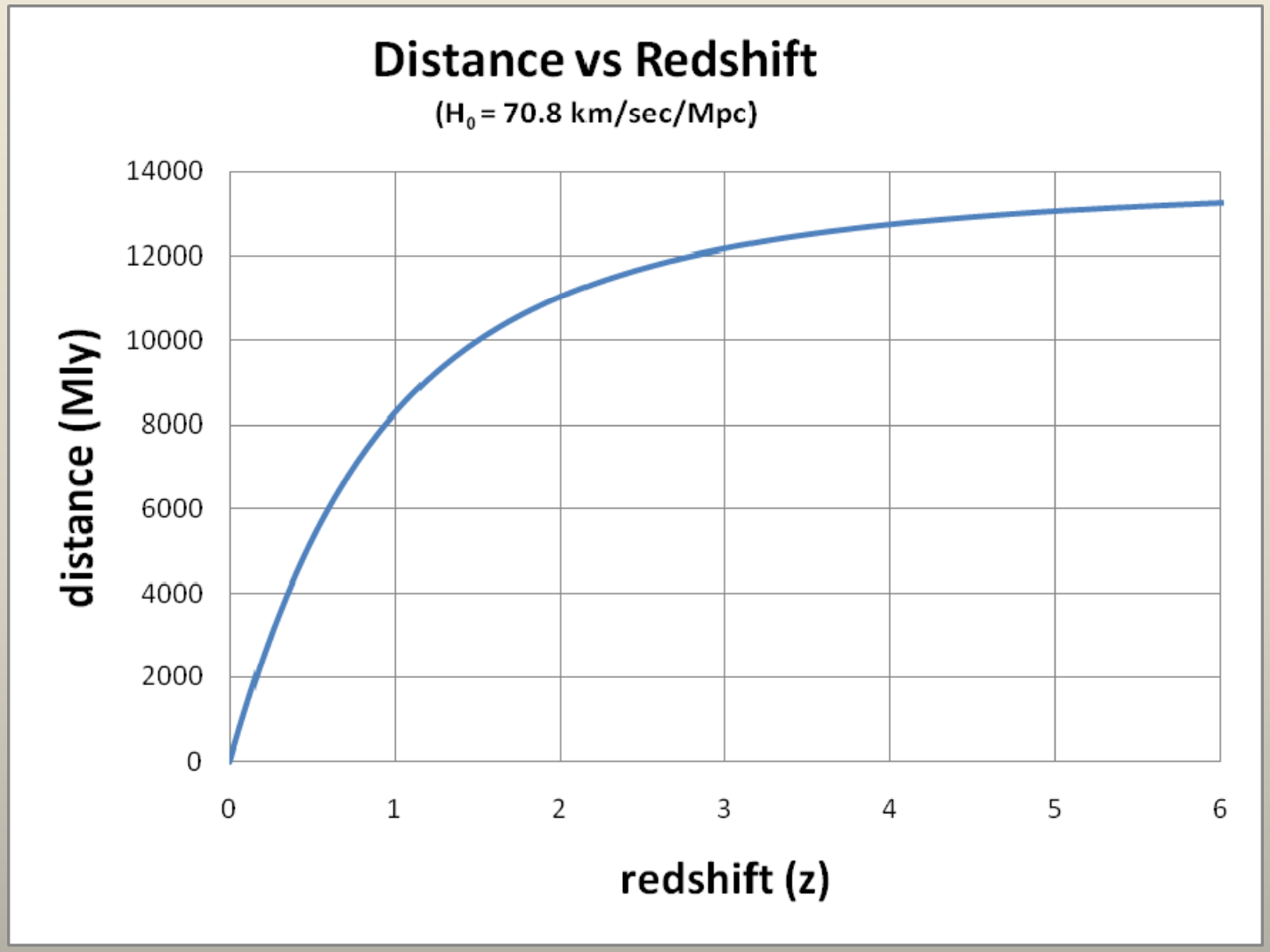
Lyman Break Galaxy (LBG) in Pisces



Spectrum w 2.5m SDSS telescope

Calculation of the redshift (z)

- Observed H_α: $\lambda = 9060$ Å
- H_α rest wavelength: $\lambda = 6562$ Å
- $z = (9060/6562) - 1 = 0.380$



(distance = c * look-back time)

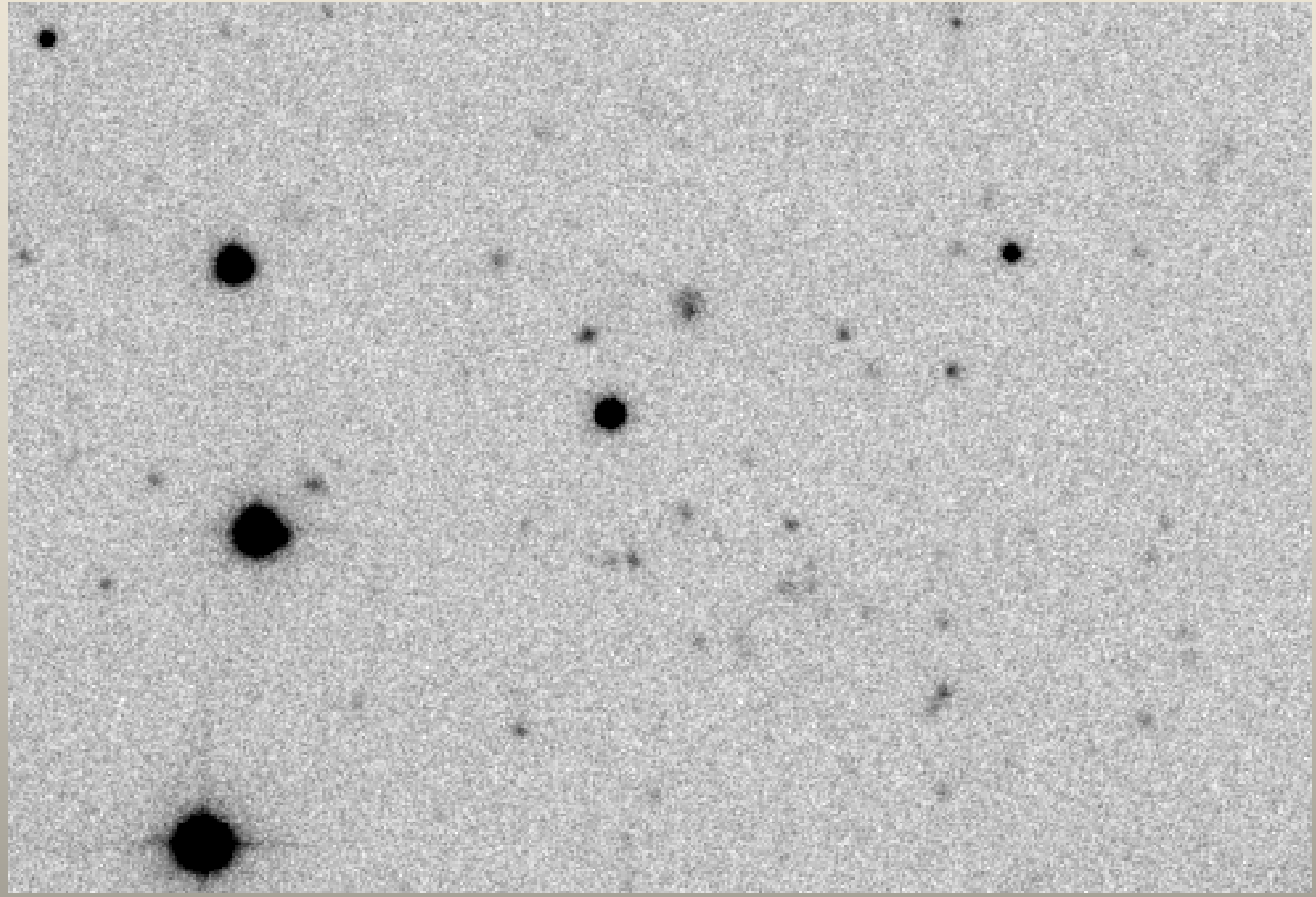
Lyman Break Galaxy (LBG) in Pisces

- Arc is distorted image of a Lyman Break Galaxy (LBG) at $z = 2.73$ (d ~ 12 Gly) - a star-forming galaxy at ~20% of Hubble time; intrinsically very luminous (~6 x L_*)
- The LBG is rendered visible (mag~21) by its luminosity and by strong lensing by foreground Luminous Red Galaxy (LRG) (mag~19) SDSS J002240.91+143110.4 at $z = 0.38$ (dist ~ 4.3 Gly)

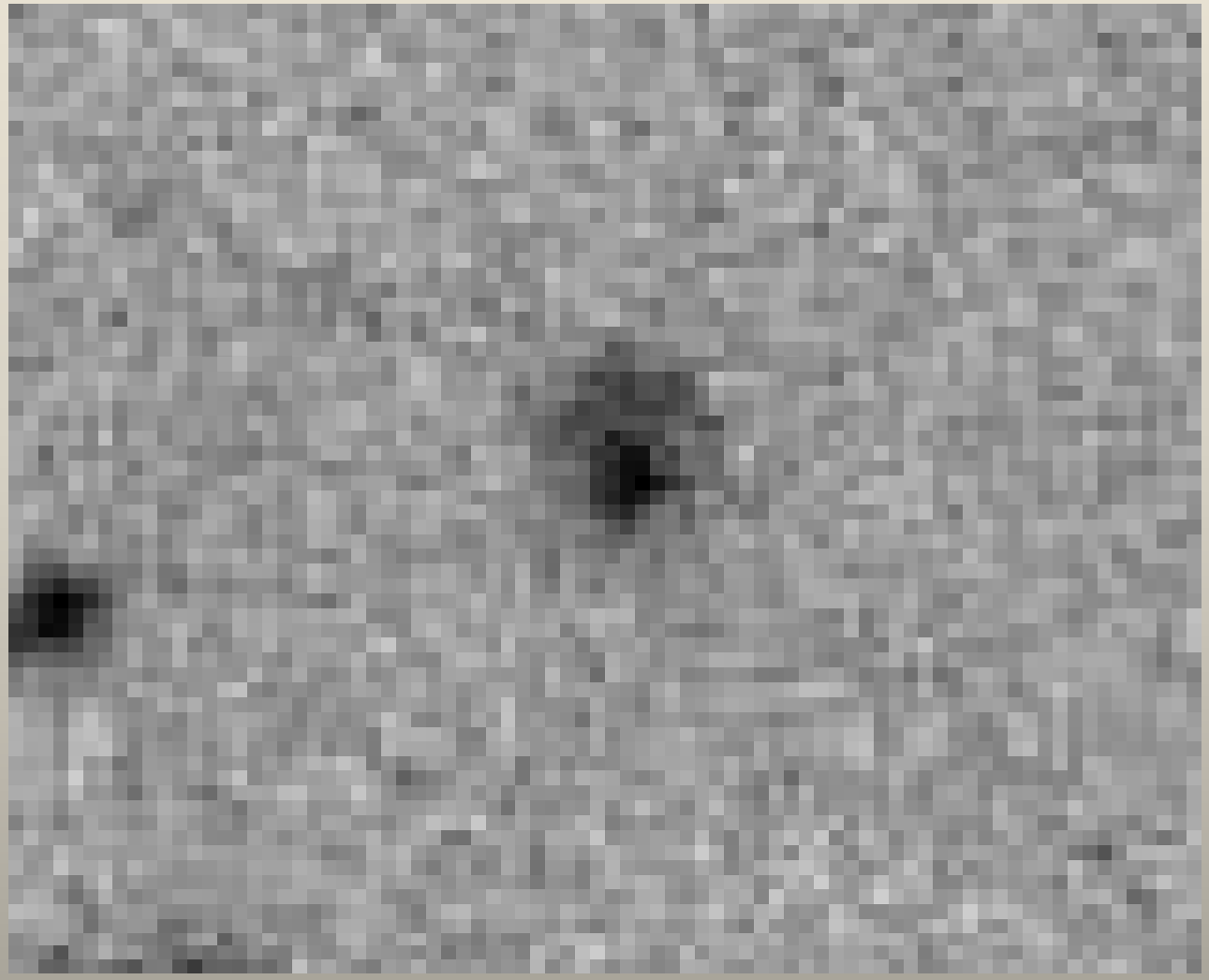
Lyman Break Galaxy (LBG) in Pisces

Exposure = 31 x 5 min

Lyman Break Galaxy (LBG) in Pisces



Lyman Break Galaxy (LBG) in Pisces



Lyman Break Galaxy (LBG) in Pisces