Lenses as cosmological telescopes - tutorial

Hands-on Strong Gravitational Lensing School, June 14, 2011

Exercise 1: Photometric redshifts

In this example we use real data observed for the 8 o'clock arc (SDSS J002240.91+143110.4). The name also refers to its J2000 coordinates. The image in Fig. 1 is composed by 3 broad band HST images (F450W, F606W, and F814W). Assume that you don't already know the redshifts, even though these are easily found online. Note that all the numbers below are mean to illustrate the methods, and are not necessarily the same as found in refereed papers in the literature (more accurate numbers can be found in Dessauges-Zavadsky et al 2011, MNRAS in press).

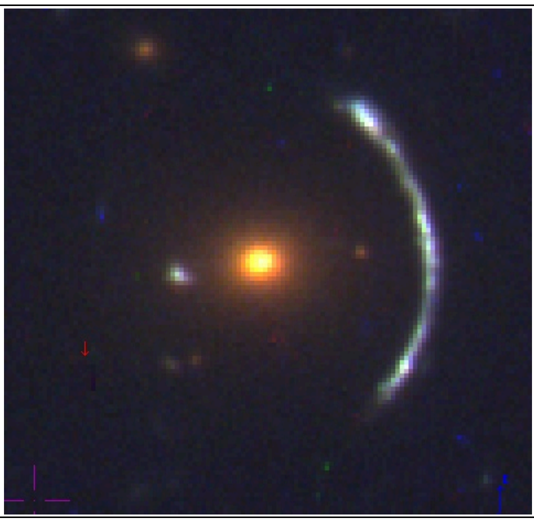

Fig1: image of the 8 o'clock arc

Table 1: Lens galaxy photometry: HST+WFPC2 and NICMOS data

F450W	23.50+/-0.10
F606W	21.70+/-0.05
F814W	20.69+/-0.05
F110W(Nicmos)	19.62+/-0.08
F160W(Nicmos)	19.03+/-0.07

Magnitudes are in the AB system.

1) Find additional photometry in the SDSS database for the lens. (http://www.sdss3.org/dr8/data_access.php)
   Use the 'Navigate' link and then 'PhotoObj'
   Use the model magnitudes. Are these magnitudes in the Vega or AB system? Be careful when mixing photometry from different resources e.g. HST and SDSS, because the apertures may be different. When you measure the

photometry from fits images, be consistent with the apertures. Why is this important?

Definition of magnitude systems, and how to convert fluxes to magnitudes in a given filter. $T\nu$ and $T\lambda$ are the transmission function of the filter.

- standard system

$$m(\star) = -2.5 \log_{10} \frac{\int F_\lambda(\star) T_\lambda \, d\lambda}{\int F_\lambda(\text{Vega}) T_\lambda \, d\lambda} + 0.03 \qquad \text{(i.e., the magnitude of Vega is 0.03)}.$$

- AB system

$$m_{\text{AB}}(\star) = -2.5 \log_{10} \frac{\int F_\nu(\star) T_\nu \, d\nu}{\int T_\nu \, d\nu} - 48.60 \qquad (F_\nu \text{ in erg.s}^{-1}.\text{cm}^{-2}.\text{Hz}^{-1}).$$

2) Determine the reddening E(B-V) by dust in our galaxy in the direction of the galaxy coordinates
(use NED: http://ned.ipac.caltech.edu/)

3) Determine the photometric redshift : http://www.iap.fr/pegase/zpeg/ (for simplicity assume the near-IR bands are similar to the Bessel filters).

4) Investigate the effect on the photo-z when the photometric errors increase, and if you have fewer filters available. For example, remove the blue-most filters/red-most filters. Inspect the output plots, and note down the best-fit physical paramters.
How sensitive is the photo-z to the chosen spectral synthesis templates?
How accurate photometry and how many bands, as well as which ones are needed to determine photo-z?

5) Find the lens galaxy size in the SDSS database

Exercise 2 : Source galaxy photo-z

Dessauges-Zavadsky et al. 2011 report AB magnitudes for two of the lensed images, within a 1 arcsec aperture.

Table 1. HST and Spitzer photometry of the 8 o'clock arc images A2 and A3

Filter	Band	A2 AB magnitude	A3 AB magnitude
F450W	*B*	21.94 ± 0.10	22.04 ± 0.10
F606W	*V*	21.36 ± 0.10	21.37 ± 0.10
F814W	*I*	21.10 ± 0.10	21.21 ± 0.10
F110W	*J*	21.12 ± 0.10	21.27 ± 0.10
F160W	*H*	20.77 ± 0.10	20.83 ± 0.10
F160W – 3.6 μm	IR color	0.61 ± 0.12	
F160W – 4.5 μm	IR color	0.93 ± 0.12	
F160W – 5.8 μm	IR color	0.94 ± 0.12	
F160W – 8.0 μm	IR color	0.78 ± 0.12	

Notes. The tabulated AB magnitudes of A2 and A3 correspond to the total photometry of the components main+blob as defined in Sect. 3.2.

1) Determine the photometric redshift of the source, note down the physical parameters besides photo-z. Does A2 and A3 give the same results?

2) What is the effect of eliminating some of the bands (for example the red-most ones)?

Exercise 3: Spectroscopic analyses

1) Look at the SDSS spectrum of the 8 o'clock lens, and determine the spectroscopic redshift.

2) Determine the Luminosity distance and absolute Luminosity in the rest frame B band at ~4500A. Use for example a cosmology calculator for this: http://ned.ipac.caltech.edu/help/cosmology_calc.html
Choose your favourite cosmological parameters for Omega_L,M and H_0

3) The observed Gauss FWHM of the CaII 3969 line is measured to be ~21.8 A. A K0 star used for reference has FWHM=13 A. The spectral resolution of the star spectrum is R~2200.
Do you have to correct for the observed SDSS spectral resolution?
Determine the stellar velocity broadening σ in km/s.
Determine the dynamical mass (in units of solar masses) of the Lens galaxy.
Determine the mass-to-light (M/L) ratio in solar units.

Exercise 4: Physical properties of the source galaxy

The source galaxy has many emission lines as listed below. The source is magnified by a factor of ~5 by the lens. The half light radius is measured in HST images to be 1.8 kpc. The FWHM of the Halpha line is 17.9 A.

Line	λ_measured	*F*tot (erg/cm2/s)
[O II] 3727	13914.8	32.9 ± 2.7
[O II] 3729	13927.3	29.1 ± 1.8
[Ne III] 3870	14448.3	11.0 ± 0.6
Hdelta	15321.7	8.5 ± 0.6
Hgamma	16212.5	17.9 ± 0.4
Hbeta	18159.7	46.0 ± 2.7
[O III] 4959	18521.5	50.5 ± 4.7
Halpha	24513.4	181.2 ± 9.6
[N II] 6585	24589.0	19.5 ± 3.7

1) Determine the spectroscopic redshift, and luminosity distance D_L
Note: the listed lines are all in the near-IR spectrum, where there are strong sky emission lines and absorption lines from the atmosphere, which makes some of the lines less reliable. If there are outliers among the lines, this may be the reason.

2) Determine the gas density from the [OII] line ratio (http://stsdas.stsci.edu/nebular/). How sensitive is the result to the assumed temperature?

3) Determine the intrinsic reddening, *E(B-V)* from various Balmer line ratios Compare with the results from exercise 2. Do they agree?

4) Correct the Halpha and [OII] emission line fluxes for the extinction

5) Determine the intrinsic star formation rate from the Halpha luminosity and [OII] lines. Do these values agree?

6) Determine the galaxy dynamical mass from the Halpha line width.

7) Determine the specific star formation rate (SFR/total stellar mass) as a proxy for the formation time for the galaxy.

8) Determine the oxygen abundance: 12+log(O/H) relative to the solar value using strong emission line diagnostics (Note: The emission line ratio [OIII] 5007/[OIII] 4959 =3 is set by atomic transition probabilities)