A Spectroscopically-Confirmed Double Source Plane Lens in the HSC SSP


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Strong Gravitational Lensing

• Background object (source) magnified by foreground object (lens)
• Multiple images → create lens model
• What can we learn from lensing?
  - total mass (within Einstein radius)
  - mass profile slope
  - ellipticity/orientation
  - substructure (both luminous and dark)
  - intrinsic (unlensed) source flux
  - can detect/resolve source features by taking advantage of magnification
  - cosmology from time-delay lensed quasars (e.g., Suyu+2016, Wong+2016, Bonvin+2016)
• Surveys to build statistical samples of lenses (e.g., SLACS, SL2S, BELLS)
  - Mostly $z \approx 0.4$, up to $z \approx 0.8$
  - need deep, wide-area, high-resolution surveys to improve statistics, especially at higher $z$
Discovering New Lenses with HSC

• Hyper Suprime-Cam SSP
  - 1400 deg$^2$ grizy imaging to $r_{AB}$~26
• ~30 group/cluster lens candidates
  - found through inspection of CAMIRA clusters (Oguri 2014)
• Survey of Gravitational lens Objects in HSC Imaging (SUGOHI)
  - 10 definite galaxy-scale lenses
  - 36 probable lens candidates
• ~10 lensed quasar candidates
  - CHITAH algorithm (Chan+2015)
• Many lenses found serendipitously
  - potential to discover exotic lenses
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More et al. (in prep)
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Double Source Plane Lenses

• Double source plane (DSP) lenses
  - two sources at distinct redshifts being lensed by the same galaxy
  - extremely rare, only a handful known (e.g., Gavazzi+2008, Tu+2009)

• Constraints from DSP lenses
  - can constrain $\Omega_m$ and $w$, independent of $H_0$ (e.g., Collett+2012, 2014)
  - can break model degeneracies (although see Schneider 2014), constrain mass structure, IMF (e.g., Sonnenfeld+2012)
Discovery of the First DSP Lens in the HSC SSP

- Double source plane (DSP) lens serendipitously discovered in HSC SSP
  - inner arc and counterimage (S1)
  - outer Einstein ring with central knot (S2)

- All redshifts spectroscopically confirmed from Magellan/FIRE observations
  - $z_L = 0.795$
  - $z_{S1} = 1.30$
  - $z_{S2} = 1.99$
  - first known DSP lens with both source redshifts spectroscopically confirmed

Tanaka, Wong, et al. (2016)
The “Eye of Horus”
The “Eye of Horus”
Ancient Eye in the Sky

July 25, 2016

Light from a distant galaxy can be stretched and bent by the gravitational influence of a foreground galaxy. This effect is called gravitational lensing. Normally, a single galaxy is lensed at a time, so the same foreground galaxy cannot simultaneously lens multiple background galaxies. However, extremely rare, such a lens system offers a unique opportunity to probe the fundamental physics of galaxies and, in theory, to test our understanding of cosmology. One such lens system has recently been discovered, and the discovery was made not in an astronomer’s office but in a classroom. It has been dubbed the “Eye of Horus” (Fig. 1) and this ancient eye in the sky will help us understand the history of the universe.

Figure 1: Eye of Horus in public view Enlarged image of the ‘eye’ field of view of 20 arcminutes x 10 arcminutes showing two anchoings with different colors. The inner arc has a reddish hue, while the outer arc has a blue hue. These arcs are lensed images of the two background galaxies. There are blurs in red around the anchoings, which are also the lensed image of these background galaxies. The yellowish object at the center is a massive galaxy at z~1.5 (6 billion light years), which bends the light from the two background galaxies. This well-focused image in the background is born. Enlarged image of the eye of Horus is from and the image with labels by NAOJ. (Credit: NAOJ)

http://naoj.org/Pressrelease/2016/07/25/index.html
A Closer Look Into the Eye of Horus

- S1A has slight velocity offset
  - rotating disk?
- Features F and G at $z \approx 1.99$, but slightly offset from rest of S2
  - S2 could be interacting galaxy pair
- One of the images of S2 is split into two distinct peaks (A+C)
  - suggests mass structure causing image splitting
  - no evidence of a galaxy between A and C from ground-based data, need higher resolution

Tanaka, Wong, et al. (2016)
Modeling the Eye of Horus

• Eye of Horus is a “compound” lens
  - S2 is being lensed by both the main lens galaxy and by S1
  - recursive multi-plane effects

• Preliminary models using HSC data
  - broadly reproduce main features
  - require additional mass component to split A+C into two images

• Need higher-resolution data (e.g. HST, ALMA, AO) for better constraints
  - ALMA Cycle 4 observations scheduled

• Lens might be in a cluster, need to include environment effects
  - existing multi-object spectroscopy of nearby galaxies
  - proposed X-ray observations with XMM to probe cluster environment
Science Goals

- Cosmological constraints, complementary to CMB, BAO, time-delay lenses
- Mass structure of lens
  - constrain stellar IMF of early-type galaxy at z~0.8
  - structure of satellite galaxy from analysis of high-resolution imaging
- High-resolution studies of source galaxies with ALMA
- Expect to find ~10 DSP lenses in HSC survey, will improve statistics

Simulated HST image

Image credit: A. Sonnenfeld

Expected location of mass substructure

Image credit: A. More
Summary

- HSC SSP will discover hundreds of new lenses at galaxy and group/cluster scales
- Discovery of the “Eye of Horus”, the first double source plane lens found in the HSC SSP (Tanaka, Wong, et al. 2016)
- Eye of Horus is the first DSP lens with all redshifts spectroscopically confirmed
  - $z_L = 0.795$, $z_{S1} = 1.30$, $z_{S2} = 1.99$
- Possible substructure causing additional image splitting of A+C
- High-resolution data (e.g., HST, ALMA, AO) needed for more detailed modeling
  - Upcoming ALMA Cycle 4 observations scheduled
- Modeling efforts will make this system useful for cosmology and galaxy evolution studies