The SDSS Quasar Lens Search

Naohisa INADA

K RIKEN K

and

The SDSS Lensers

The Sloan Digital Sky Survey: from Asteroids to Cosmology
15 August 2008 @ Chicago Merchandise Mart
Motivation-1

**Lensed Quasars** are unique tools for ..... 

- **individual mass models**
  mass distribution & substructure of lensing galaxies.
- **absorption lines in multiple QSO images**
  interstellar medium of lensing galaxies.
- **microlensing**
  host galaxies & accretion disks of source QSOs.
- **statistics, time delay**
  cosmology.... dark energy, Hubble constant.
- **cluster scale lensed quasars**
  dark matter distributions in galaxy clusters.
Motivation-2

~100 lensed quasars have studied with various methods and wavebands. In particular, the CLASS, the HST survey, etc. have done great works but ….

- lack of *completely* homogeneous and large statistical samples.

2. lack of “cluster-scale” lensed quasars.

To construct the largest lensed quasar catalog, we are now carrying out “The SDSS Quasar Lens Search (SQLS)”.

The 100,000 spectroscopically confirmed SDSS Quasars will allow us to make the largest complete statistical sample, and the first discovery of cluster scale lensed quasars.
### Problem for Searching LQs in the SDSS

A serious problem for searching lensed quasars in the SDSS data is ….

<table>
<thead>
<tr>
<th><strong>Parameter</strong></th>
<th><strong>Value</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>pixel scale of images</td>
<td>0.4&quot;</td>
</tr>
<tr>
<td>typical seeing size of</td>
<td>~1.3&quot;</td>
</tr>
<tr>
<td>spatial resolution of spectroscopy</td>
<td>3.0&quot;</td>
</tr>
</tbody>
</table>

- **typical separation of lensed quasars is** K~1.0”

We developed a selection algorithm based on the nature of the first SDSS lensed quasar, **J1226K0006**, which has been **manually** discovered from the SDSS commissioning data.
We have surveyed 90% of the SDSS data, ~90,000 QSOs. We use morphologies for unresolved (K ≤ 2.5") objects and colors for deblended (K ≤ 2.5") objects.

~600 candidates. ~100 objects have no follow-up obs.

We then conduct follow-up observations for the candidates.

Confirmation is made by both existences of lensing objects AND identical SEDs of lensed images.
Completeness of our Selection Method

**double lenses:** 95%, 90%, 75%, 50%, 25%, 10%, 5%.

*complete for* \( f > 0.32 \) \( \text{and} \) \( m > 1.0" \)

**quadruple lenses:** blue solid line. (red dotted line is completeness for doubles.)

*complete for* \( m > 1.0" \)
Results!

32 new = 27(2)+5(4)
11 known = 8(2)+3(4)
From the discoveries, we constructed our first statistical sample for quasars of the SDSS Data Release 3.

Source: 22,683 QSOs from the SDSS DR3 (with 0.6 < z < 2.2, i < 19.1, and seeing < 1.8")

Candidate: total 220 candidates (90 by morphology, 132 by color, 2 duplicates)

Lenses: 22 lensed quasars. 11 lenses are in our “complete” survey region, 1.0” < K < 20.0” and f > 0.32.

for w_K1 : $K_K = 0.74$

for w_K K1 : $K_m = 0.26$

w = $K_1.1$
Discovery of 2 Cluster Scale Lenses

We have succeeded in discovering two cluster-scale lensed quasars!

SDSS J1004+4112

$HST$, $K_s \approx 14.6''$, $z = 1.73$, $z_L = 0.68$

The first cluster-scale lens!!

They support the CDM, statistically and individually.

SDSS J1029+2623

$Keck$, $\theta = 22.3''$, $z_S = 2.20$, $z_L = 0.60$

3 images by a naked cusp
Discoveries from SDSSJ1004+4112

Chandra image K

HST image K

$K_{AB} = 40.6$

$K_{AC} = 821.6$

Fohlmeister et al.
Summary

• We are now carrying out “The SDSS Quasar Lens Search, which discovered 32 lensed quasars, including 2 cluster-scale lensed quasars with large separations. The SQLS is the current largest lensed quasar survey!

• From these discoveries, we have completed our first statistical sample from the SDSS DR3. The constraint for dark energy is consistent with the results from SN survey and WMAP.

• At the end of the SDSS (I &II), we are completing our lensed quasar survey. The statistical sample from DR5 is coming soon, and the final statistical sample from DR7 is expected to be constructed within a few years.
References

slide-2:
Kochanek 2006, Proceeding (Saas-fee)
and MANY

slide-3:
Schneider et al. 2007, AJ, 134, 102

slide-4:
None

slide-5:

slide-6:

slide-7
none

slide-8:
Inada et al. 2003, AJ, 126, 666
Inada et al. 2006, AJ, 131, 1934
Inada et al. 2007, AJ, 133, 206
Kayo et al. 2007, AJ, 134, 1515
Morokuma et al. 2007, AJ, 133, 214
Oguri et al. 2004, PASJ, 56, 399
Pindor et al. 2006, AJ, 131, 41
and MANY

slide-9:

slide-10:
Inada et al. 2003, Nature, 426, 810

slide-11:
Inada et al. 2005, PASJ, 57, L7
Sharon et al. 2005, 629, L73
CLASS:
22 lenses from 16,000 radio sources.
(13 statistical sample from 8,958 radio source)

HST Snap Shot Survey:
3~6 lenses from 500 quasars.
SDSS spectroscopic QSO catalog

construct statistical subsample:
15.0 < i_cor < 19.1, 0.6 < z < 2.2, & PSF_WIDTH_i < 1.8''

source QSOs

morphological selection:
condition M1, M2, or M3
Yes
parent morphological candidates

GALFIT fitting:
selection criteria of S1
Yes
visual inspection
more than 2 stellar components
final morphological candidates
for follow-up

No
reject

color selection:
condition C1 or C2
Yes
parent color candidates

inconsistent radio flux ratio
No
FIRST image check

clearly QSO+galaxy
consistent radio flux ratio

No
reject

visual inspection
more than 2 stellar components
searching for possible lensing objects

No
not lens

Yes
final color candidates
for follow-up

similar SED and lensing object detection
confirmed lensed QSOs
for $w = K_1$: $K_K = 0.74 \pm 0.11_{\text{stat}} \pm 0.13_{\text{syst}}$

for DE: $w = K_{1.1} \pm 0.6_{\text{stat}} \pm 0.3_{\text{syst}}$

$K_M = 0.26 \pm 0.07_{\text{stat}} \pm 0.03_{\text{syst}}$
Large-Separation ($\theta > 7''$) Lensing Probabilities of QSO with Redshift $z = 2.0$ and Magnitude $m_i = 19.0$

$\Omega_M = 1 - \Omega_\Lambda = 0.27$

$\sigma_8 = 1$

$c_{-2}/c_{-2}(\mathrm{CDM})$

$\alpha$

SDSS

SIDM ($\alpha > 0.1 \, \mathrm{cm}^2 / \mathrm{g}$)

WDM ($m_i < 1 \, \mathrm{keV}$)

CDM

Contour lines indicate different lensing probabilities.
$K^K : K K^{0.5} < 1.0$ (SIS)