Multi-Sightline Spectroscopy of Outflowing Winds in Quasar SDSS J1029+2623

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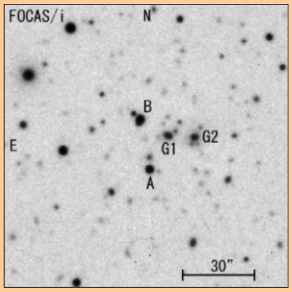
SUMMARY: Accretion disk outflows, powered by various mechanisms, are the most important key ingredient for the evolution of quasars as well as for galaxy formation and evolution. Broad absorption lines (BALs) observed in quasar spectra are known to be a powerful tool to probe the outflows of quasars, but we have opportunities to trace only single sight-lines for each quasar so far, i.e., we do not have any "eyes" to see the 3-D structure of the outflows. The recent discovery of the large-separation lensed quasar SDSS J1029+2623 (z_{em} ~ 2.197), with separation angle of 22".5 (lensed by a massive "cluster of galaxies") provides a chance to see the outflow of a quasar in multiple viewing-angles, through the C IV BAL-like feature in each lensed image. We carried out medium-resolution spectroscopy of the two brightest images of the quasar (images A and B, hereafter) to see whether the BAL-like features are variable or not, and also high-resolution spectroscopy to extract line parameters to place strict constraints on the absorber's physical conditions. Our results support that we really observe different regions of the outflowing wind toward multiple sight-lines.

LENSED QSO SDSS J1029+2623

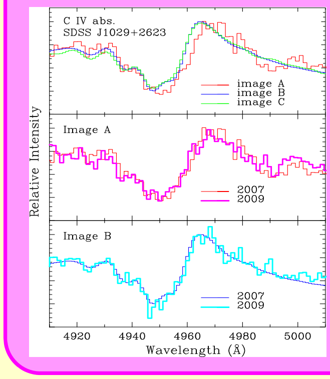


The largest-separation lensed quasar, SDSS J1029+2623, was discovered by Inada et al. (2006) (Figure 1). As shown in Figure 2, lensed images A and B (A being the brightest) have BAL-like features with different profiles at the blue-wing of the C IV emission line, which strongly supports that each sight-line passes through the outflowing wind.

Fig.1: An *i*-band image of SDSS J1029+2623 taken with Subaru/FOCAS (Inada et al. 2006). Two objects labeled with A and B, with an angular separations of ~22".5, are lensed images of the quasar.

WHY ABSORPTION LINES ARE DIFFERENT?

The following implications can explain the difference of absorption profiles: (i) this is due to the time variability of an identical absorber because the time-delay between images A and B is ~1860 days (hereafter, scenario A), (ii) we see different regions of the outflowing wind toward multiple sight-lines as proposed in Green (2006; scenario B). To test the time-variation scenario, we performed an additional spectroscopic observation of the lensed images A and B with Subaru/FOCAS, using a similar resolution as the previous observations (R~500). In a time separation of 2-3 years, comparable to the time delay between images A and B, we did not see any clear time variation in either image (see Figure 2), which suggests the scenario A is less favorable.



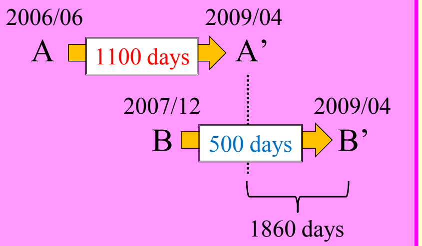


Fig.2: (Top) Expanded spectra (R~500) of images A, B, and C (the faintest one) of SDSS J1029+2623 (Inada et al. 2006; Oguri et al. 2008). Image A has broader and smoother line profile with an additional narrow line at ~4990Å. (Middle and Bottom) Test of time-variation for spectra of images A and B in time intervals of 2-3 years.

INTRINSIC OR INTERVENING ABSORPTION?

Next, we took high-resolution (R~30,000) spectra of the images A and B with Subaru/HDS, and noticed that the BAL-like features were separated into several narrower lines (i.e., NALs). While BALs have high probability of being physically associated to the quasars, NALs are arising not only at outflowing winds (we call them "intrinsic" NALs) but at cosmologically intervening structures such as ISM, IGM, or foreground galaxies (we call them "intervening" NALs).

With these high-resolution spectra, we concluded that the clustering of NALs seen in our spectra indeed have intrinsic origin because of three observational evidences:

(1) These NALs have small ejection velocities from the quasar (Figure 3). Wise et al. (2004) found that high fraction (~21%) of the associated NALs, within 5,000 km/s from the quasar systemic redshift, is time-variable, (i.e., intrinsic NALs).

(2) These NALs show line locking phenomenon (i.e., weak components of C IV doublets are aligned with strong ones of next doublet; Figure 3), which is naturally explained by radiative acceleration (Perry et al. 1978; Weymann et al. 1981).

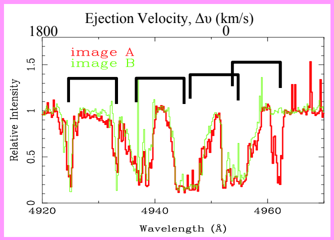
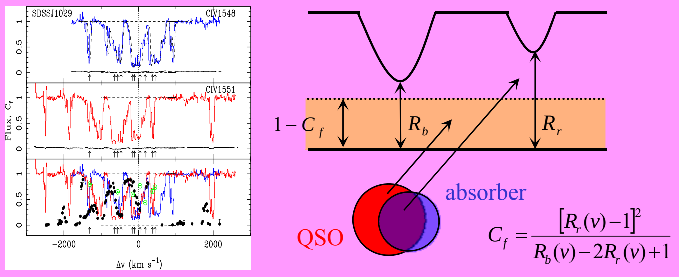


Fig.3: Normalized spectrum around the clustering of C IV NALs in the images A (red) and B (green) along with wavelength (bottom) and ejection velocity from the quasar systemic redshift (top). Their general profiles are similar each other although showing clear differences such as peaky residual fluxes around the bottom of absorption lines. At least four C IV doublets (marked with black lines above the spectra) show the line locking phenomenon.

(3) These NALs show evidence of partial coverage (i.e., trough dilution by unocculted light toward background source (e.g., Wampler et al. 1995) (Figure 4).



$$C_f = \frac{[R_r(v) - 1]^2}{R_b(v) - 2R_r(v) + 1}$$

Fig.4: (Left) A clustering of C IV NALs has clear partial coverage. (Right) The optical depth ratio of C IV doublet sometimes deviates from the values expected from atomic physics, 2:1. This can be explained by partial coverage. A coverage fraction, C_f, is calculated by the equation.

INTERNAL STRUCTURE OF OUTFLOWING WIND ~ FILAMENTARY STRUCTURE ~

From the high-resolution spectra taken with Subaru/HDS, we learned the following things:

1) NAL absorbers in the outflowing wind show a clear partial coverage, which means the physical scales of NAL absorbers and/or their density fluctuation should be comparable to or smaller than the size of the background continuum source of the quasar. This size is typically ~10^{-3} pc for luminous quasars like our target.

2) Absorption profiles seen in the images A and B are similar to each other, which means that their sight-lines trace a common absorbing structure. A filamentary structure could be the absorber, because hydrodynamical simulations sometimes produce filamentary structure above the main body of the outflow as shown in Figure 5 (e.g, Ohsuga et al. 2005; Proga et al. 1998, 1999).

A physical distance between the sight-lines, *D*, depends on the absorber's distance from the continuum source, *r*. However, we have only loose constraints on it, spanning from *r* = 0.01 to 1000 pc (e.g., Elvis 2000; de Kool et al. 2001). Thus, a corresponding scale of *D* would be 10^{-6} to 0.1 pc. For more stringent constraints, we need to perform photoionization modeling.

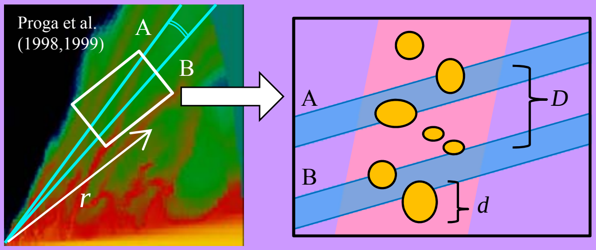


Fig.5: (Left) Density map for a time-dependent two-dimensional radiation-driven disk wind model (Proga et al. 1998,1999), with possible sight-lines for the images A and B of the quasar. (Right) Cartoon of our hypothesis that the two sight-lines (blue belts), being separated by *D* each other, are going through a same filamentary structure (pink belt) containing many clumpy clouds with typical size of *d*.

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