CO Emission from z~6 Quasars: Black Hole, Bulge and Dynamical Masses

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CO in $z=6.42$ quasar J1148+5251

- CO Flux density peak at $\sim J=6$
- SFR $\sim 3000 \, M_\odot/yr$
- 2 component morphology
- $H_2$ mass $= 1 \times 10^{10} \, M_\odot$
- BH mass $\sim 10^9 \, M_\odot$
  (Willott et al.)
- $\sigma \sim 120 \, \text{km/s}$ linewidth $= 5 \times 10^{10} \, M_\odot$ dynamical mass
- (no $10^{12} \, M_\odot$ bulge?)

$M_{BH} \approx 0.002 M_{\text{star}}$

Quasars $z \sim 6$

Walter et al., 2004
Bertoldi et al., 2004
z~6 Quasar Formation Simulations

- Structure Formation models to identify most massive halo

- Resimulate most massive halos \((10^{12}-10^{13} M_{\odot} \text{ at } z=6)\) to derive merger tree

- Hydrodynamically simulate galaxy mergers: GADGET-2

- 3 galaxies chosen for this study \((10^{12}-10^{13} M_{\odot} \text{ at } z=6)\)

  Y. Li et al (2007a,b)

  Y. Li et al. in prep
So why are the observed line widths so narrow?
Non-LTE Radiative Transfer

- 3D Monte Carlo code developed based on improved Bernes (1979) algorithm
- Benchmarked against Leiden non-LTE radiative transfer tests
- Sub-grid algorithm considering mass spectrum GMCs as SIS
- $M_{\text{cloud}} = 10^4 - 10^6 M_\odot$, Galactic CO Abundance, 10 CO transitions, 10 million rays per iteration

Gas-rich Spiral Example CO J=1-0

Narayanan et al. 2007
CO (J=3-2) Morphology - Good Correspondence with Observations

Simulations

Observations (VLA)

Narayanan, Li, et al. 2007

Walter et al. (2004)

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CO Excitation: CO SEDs

Simulations

Observations

J=6 Peak

DN + (2007)

Bertoldi et al. (2004)
CO Emission Lines

Large virial velocities in massive halo ($\sigma \sim 300-800$ km/s) manifested in large CO line widths

$\sigma = 800$ km/s

$\sigma = 500$ km/s

$\sigma = 300$ km/s

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CO Emission Lines

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Bertoldi et al.; Walter et al
Sightline-Dependent CO Line Widths: Most Extreme Halo as an Example

1. Large range of line widths permitted owing to different viewing angles of molecular disk

2. Time Evolution in mean sightline-averaged CO line width

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Sightline-Dependent CO Line Widths: Most Extreme Halo as an Example

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Optically Luminous LOSs have small CO FWHMs because of molecular disk formation.
Selection Effect

Highest B-band Luminosities have higher percentages of compatible sightlines because of selection effects:

10-25% of sightlines compatible with observations (Halo Mass Dependent)
Observable Tests (How Have We Gotten Here?)

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Observable Tests:

1. Line widths of future $z \sim 6$ quasar detections (should be broad(er)!) 

2. Line widths of galaxies and quasars which form in comparable $10^{12} - 10^{13} \, M_\odot$ halos at $z \sim 2$ (SMGs, $z=2$ QSOs)
1. Line widths of lower luminosity $z \sim 6$ quasars (should be broad(er)!!)

2. Line widths of galaxies and quasars which form in comparable $10^{12}-10^{13} \, M_\odot$ halos at $z \sim 2$

Carilli et al. (2007)

Maiolino et al. (2007)
Observable Tests:

1. Line widths of lower luminosity $z\sim6$ quasars (should be broad(er)!!)

2. Line widths of galaxies and quasars which form in comparable $10^{12}-10^{13} M_\odot$ halos at $z\sim2$

\[ \text{FWHM (z=2)} = \frac{\sqrt{1+z=2}}{\sqrt{1+z=6}} \times \text{FWHM (z=6)} \]

z~2: Carilli & Wang 2006
Observable Tests:

1. Line widths of lower luminosity z~6 quasars (should be broad(er)!) 

2. Line widths of galaxies and quasars which form in comparable $10^{12}-10^{13} \, M_\odot$ halos at $z\sim2$

1. $z\sim2$ Quasar line widths natural with redshift evolution of potentials for $10^{12}-10^{13} \, M_\odot$ halo

2. SMG line widths natural for temporal evolution of line widths in $10^{13} \, M_\odot$ mergers at $z\sim2$
Conclusions

• Merger driven model for z~6 Quasar formation which lies on the present-day Magorrian relation well supported by simulated CO morphology and line widths

• CO emission line widths in first quasars predicted to have $\sigma =300-500$ km/s if qso’s form in massive halos, consistent with virial velocity of halo

• Molecular Disk formation may bias optically selected quasars toward narrow CO line widths

• Linewidths of z~2 qso’s and SMGs naturally explained in this model