Extended Emission-Line Regions: Remnants of Quasar Superwinds?

Hai Fu
University of Iowa

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Outline

- History (1975–2005) and Motivation
- Integral Field Spectroscopy of Extended Emission-Line Regions (EELRs)
- EELR–Quasar Metallicity Relation
- Star Formation in the Host Galaxies
- Answers to Previous Questions
The Discovery of 3C 273: The First Quasar

Edge et al (1959) - 1′

Hazard et al (1963) - Occultation, 1″

Schmidt (1963)

13-mag “star”
Quasar’s Rapid Variation
Discovered by Smith & Hoffleit (1963)

What Powers a Quasar?

Accreting black hole inside a giant galaxy

Hoyle et al (1964), Lynden-Bell (1969)

Type 1

Type 2
THE DISCOVERY OF
EXTENDED EMISSION-LINE REGION (EELR)

Sandage & Miller (1966)

Wampler et al (1975)

3C 48

20 kpc

[O II] 3727

Hβ

[O III] 4959

[O III] 5007
Which Quasars Have Extended Emission-Line Regions?

Boroson & Oke (1984) - A Spectroscopic Survey

<table>
<thead>
<tr>
<th>Group 1</th>
<th>Group 2</th>
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<tbody>
<tr>
<td>Blue continuum</td>
<td></td>
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<tr>
<td>Strong emission lines</td>
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<tr>
<td>No Fe II emission</td>
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<tr>
<td>Narrow lines are strong</td>
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<tr>
<td>Very broad, bumpy H lines</td>
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<tr>
<td>[O III]/Hβ large</td>
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<tr>
<td>Steep spectral index</td>
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<tr>
<td>Double lobed structure</td>
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<tr>
<td>Red continuum</td>
<td></td>
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<tr>
<td>Weak or absent emission lines</td>
<td></td>
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<td>Strong Fe II emission</td>
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<tr>
<td>[O III]/Hβ moderate</td>
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<tr>
<td>Flat spectral index</td>
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<td>Compact structure</td>
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</table>
Which Quasars Have Extended Emission-Line Regions?

Stockton & MacKenty (1983, 1987) - SM87 Sample

An [O III] Imaging Survey of 47 Quasars at z < 0.5

11 EELR Quasar  

36 non-EELR Quasar

VS
Which Quasars Have Extended Emission-Line Regions?

Stockton & MacKenty (1987)
Morphology of EELRs

4C37.43 z=0.37

4C 37.43 [O III] Emission

4C 37.43 Continuum

Stockton et al. (2002)
Morphology of EELRs

HST [O III]

20 kpc
Summary & Questions

- EELR \sim L_{[\text{O III}]}^\text{nuclear} & Radio Morphology
- Independent Morphologies of EELRs
- Photoionization by the central source

? Are EELRs shock-ionized?
? What makes EELR quasars special?
? Where did the gas come from?
? How were the EELRs formed?
Integral Field Spectroscopy of EELRs

Sketch of Gemini GMOS/IFU (Allington-Smith et al. 1998, 2002)

Telescope Focus

Spectrograph Input

Spectrograph Output

Datacube

Science Field

Sky Field

0.2" lenslets
5" x 7" FOV

slit 1

slit 2
Integral Field Spectroscopy of Quasar EELRs

Large Radio Sources (0.25 ≤ z ≤ 0.37)

- **Ton 616 [O III]**
  - CFHT
- **4C 37.43 [O III]**
  - HST WFPC2
- **3C 249.1 [O III]**
  - HST WFPC2

- **3C 79 [O III]**
  - HST WFPC2
- **PKS 2251+11 [O III]**
  - CFHT
- **Ton 202 [O III]**
  - CFHT
TANNED HIDE:
- Moccasins, Cradles, Winter Robes, Shirts, Leggings, Belts, Dresses, Pipe Bags, Quivers, Tipi Covers, Gun Covers, Dolls

RAWHIDE:
- Containers, Shields, Buckets, Moccasin Soles, Belts, Headdresses, Medicine Bags, Drums, Ropes, Saddles, Stirrups, Knife Cases, Quirts, Armbands, Bullet Pouches

MUSCLES:
- Sinew, Meat for Jerky

HORNS:
- Cups, Spoons, Ladles, Headdresses

TAIL:
- Decorations, Fly Brush, Whips

BRAINS:
- Hide Preparation

FAT:
- Soap, Cooking Oil

SKULL:
- Altar at Religious Ceremonies

BONES:
- Knives, Arrow-Heads, Shovels, Scrapers, Winter Sleds, Saddle Trees, War Clubs, Game Dice

BEARDS:
- Ornaments for Weapons

DUNG:
- Fuel

STOMACH:
- Buckets, Cups, Dishes, Cooking Pots

TONGUE:
- Best Part of the Meat

HAIR:
- Headdresses, Saddle Pad Filler, Pillows, Ropes, Halters

HOoves:
- Glue, Rattles

Graphic courtesy of South Dakota State Historical Society
Gas Kinematics
QUASAR SUBTRACTION
**Velocity Structure**

NGC 2974

Sarzi et al. (2005)

NGC 3414

Fu & Stockton (2007a)
Ionization Mechanism
Ionization Mechanisms

**Photoionization**

- by massive stars (Kewley 2001)
- by quasars (Groves et al. 2004)
Classification of Extragalactic Emission-Line Objects

Classification of Extragalactic Emission-Line Objects

Photoionized by Massive Stars? - No.

\[
\frac{[O \, \text{III}]/\text{H}\beta}{\text{vs.}} \frac{[O \, \text{II}]/\text{H}\beta}
\]

Fu & Stockton (2008b)
**Ionization Mechanisms**

- **Photoionization**
  - by massive stars (Kewley 2001)
  - by quasars (Groves et al. 2004)

- **Shock**
  - emission lines from cooling post-shock gas (Dopita & Sutherland 1996)

- **Shock+Precursor**
  - emission lines from both post-shock and pre-shock gas
Shock Ionization? - No.

[O III]/Hß vs. [O II]/Hß

Power-law Photoionization

Shock + Precursor

Shock

Fu & Stockton (2008b)
Photoionized by Quasars

\([\text{O} \text{ III}] / \text{H}\beta \text{ vs. } [\text{O} \text{ II}] / [\text{O} \text{ III}] \ \& \ [\text{O} \text{ II}] / [\text{Ne} \text{ III}]\)

\([\text{O} \text{ III}] / \text{H}\beta \text{ vs. } [\text{O} \text{ I}] / \text{H}\alpha \ \& \ [\text{S} \text{ II}] / \text{H}\alpha\)
Globally disordered kinematics
Low velocity dispersions ~ 100 km/s
Photoionized by quasar continuum
Gas pressure ~ $10^4 – 10^6$ K cm$^{-3}$
Ionized mass ~ $10^9$ M$_\odot$
Metallicity
Secondary Production of Nitrogen

\[ \frac{N}{O} \propto \frac{O}{H} \Rightarrow \]
\[ \frac{N}{H} \propto \left(\frac{O}{H}\right)^2 \propto Z^2 \]

Groves et al. (2004a)
EELR Metallicity

Fu & Stockton (2006, 2007a, 2008b)

To Lower Metallicity

Graph showing the relationship between Log$_{10}$([O III] 5007/HH$\beta$) and Log$_{10}$([N II] 6584/H$\alpha$) with various metallicities indicated, including $1/6 Z_\odot$, $1/3 Z_\odot$, $2/3 Z_\odot$, and $4/3 Z_\odot$. The graph also highlights the direction to lower metallicity with a green arrow labeled 'To Lower Metallicity'.
Quasar Metallicity from Broad-Line Region

(Hamann et al. 2002)
EELR Quasars are Metal-Poor Quasars

Figure: Fu & Stockton (2007b)

HST data:
Kuraszkiewicz et al. (2002)

[O III] imaging data:
Stockton & MacKenty (1987)
EELR quasars = Metal-poor quasars
+ lobe-dominated radio source
+ strong nuclear narrow-line emission

Nuclear $L_{\text{[O III]}}$ vs. Radio $\alpha_\nu$

- Metal-rich quasar
- Metal-poor quasar
- EELR quasar
- Non-EELR quasar

RQ  Flat Spec.  Steep Spectrum

Radio Spectral Index, $\alpha_\nu$ (400 to 2700 MHz)
Mass—Metallicity Relation from SDSS

Tremonti et al. (2008b)

12 + log(O/H) vs. log(M$_*$)

σ = 0.10

1 Solar
2/3 Solar
1/3 Solar
2.5 Solar
Origins of Metal-Poor Gas

Cold Accretion
(Keres et al. 2005)
✓ metal-poor gas in extended nebulae
● metal-poor gas in nuclear region

Merging Companion
(Stockton et al. 1983)
✓ metal-poor gas in extended nebulae
✓ metal-poor gas in nuclear region

Cooling Flow
(Fabian et al. 1987)
✓ metal-poor gas in extended nebulae
✓ metal-poor gas in nuclear region
Upper Limits on X-ray Luminosity

=> Cooling Rate < 0.7 $\text{M}_\odot$/yr ($r < 20\text{kpc}$)
The Origin of the Gas

Cold Accretion
- (Keres et al. 2005)
- ✓ metal-poor gas in extended nebulae
- ✤ metal-poor gas in nuclear region

Merging Companion
- (Stockton et al. 1983)
- ✓ metal-poor gas in extended nebulae
- ✓ metal-poor gas in nuclear region
- ✓ Low pressure in X-ray halo

Cooling Flow
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The Formation of EELRs

Tidal Interactions
Stockton & MacKenty (1983)
✓ disordered kinematics

Starburst Superwind
Stockton et al. (2002)
✓ disordered kinematics

Quasar Superwind
Di Matteo et al. (2005)
✓ disordered kinematics
HI Gas in Interacting Galaxies

Hibbard et al. (1996-2001)
# The Formation of EELRs

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Unification of Quasars & Radio Galaxies

Barthel (1989)

Radio Galaxy

Quasar
3C79: An EELR Radio Galaxy

redshift = 0.256

Fu & Stockton (2008)
3C79: Radio Morphology
3C79: Low Metalliclity

Fu & Stockton 2008, 2009a

To Lower Metalliclity

Fu & Stockton 2008, 2009a
3C79: Broad Mg II Line

Fu & Stockton (2008)
3C79: Stellar Population

Fu & Stockton (2008)

Rest-Frame Wavelength

Flux

3C79 Keck/LRIS
**3C79: Stellar Population**

Host Galaxy of 3C79

1. Age: 10 Gyr & 1.3 Gyr
2. Metallicity: 2.5 $Z_\odot$
3. Stellar Mass: $2.6 \times 10^{11} \, M_\odot$
4. Dynamical Mass: $4 \times 10^{11} \, M_\odot$
5. Morphology: Elliptical + close companion
Spitzer MIR-to-FIR SEDs of EELR Quasars

Spitzer IRS/MIPS
Fu et al. (2009b)
The Formation of EELRs

- **Tidal Interactions**
  - Stockton & MacKenty (1983)
  - ✓ disordered kinematics
  - ✤ no underlying continuum
  - ✤ high velocity clouds (v>500 km/s)
  - ✤ no significant young stellar pop.

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  - ✓ metal-poor gas in the nuclear BLR

- **Quasar Superwind**
  - Di Matteo et al. (2005)
  - ✓ disordered kinematics
  - ✓ no underlying continuum
  - ✓ high velocity clouds (v>500 km/s)
  - ✓ no significant young stellar pop.
  - ✓ metal-poor gas in the nuclear BLR
Summary

- GMOS Integral-Field Spectroscopy of 6 EELRs
- Disordered gas kinematics
- Quasar photoionization
- **Gas** (both nuclear & extended) in EELR quasars is *metal-poor*
- **Stars** in the host galaxy are *old* and *metal-rich*
Answers

? Are EELRs shock-ionized?
  • No. Quasar photoionization more likely.

? What makes EELR quasars special?
  • Gas metallicity.

? Where does the gas come from?
  • A merging gas-rich galaxy.

? How are the EELRs formed?
  • Remnants of quasar superwinds.