A Supermassive Black Hole in the Dwarf Starburst Galaxy Henize 2-10

Amy Reines
Einstein Fellow
National Radio Astronomy Observatory
Supermassive black holes and galaxy evolution

- Supermassive black holes reside in the nuclei of essentially all massive galaxies with a bulge (e.g. Kormendy & Richstone 1995; Magorrian et al. 1998; Kormendy 2004)

\[ M_{BH} \sim 1.4 \times 10^8 \, M_{\text{sun}} \] (Bender et al. 2005)

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- Did galaxies and nuclear black holes grow synchronously? If not, which developed first?
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Volonteri (2010)
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Possible seed formation mechanisms

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- What is the nature of the supermassive black hole - globular cluster connection?
“An actively accreting massive black hole in the dwarf starburst galaxy Henize 2-10”

“Astrophysics: Big black hole found in tiny galaxy”
Greene 2011, Nature, 470, 45
Henize 2-10

- Nearby ($D \sim 9$ Mpc) dwarf starburst galaxy (Allen et al. 1976)
- Compact ($\sim 1$ kpc), irregular morphology
- Young super star clusters (proto-globular clusters) (e.g. Johnson et al. 2000)
Henize 2-10

- Nearby (D~9 Mpc) dwarf starburst galaxy (Allen et al. 1976)
- Compact (~ 1 kpc), irregular morphology
- Young super star clusters (proto-globular clusters) (e.g. Johnson et al. 2000)
- Main optical body is about half the size of the SMC
- SFR ~ 10 times the LMC but similar stellar and HI masses
Observations

Infant super star clusters:
Youngest have ages \( \leq \) few Myr
and masses \( \sim 10^5 \, M_{\odot} \)

HST 3-color optical image (archival data):

- F330W (0.3 microns)
- F814W (0.8 microns)
- F658N (H alpha)
Observations

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New data

VLA 3.5 cm
HST Paschen alpha

~ 6 arcsec, 250 pc
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New focus: the central source

VLA 3.5 cm
HST Paschen alpha

~ 6 arcsec, 250 pc
The central source in Henize 2-10

Narrow-band imaging (ionized gas)
- Paschen alpha line emission (1.87 microns)
- H alpha line + continuum (0.66 microns)
- 3.5 cm contours

Broad-band imaging (stars)
- NIC2 F205W (2.1 microns)
- ACS/HRC F814W (0.8 microns)
- 3.5 cm contours
Compact (< 24 pc x 9 pc) non-thermal (synchrotron) radio emission (Johnson & Kobulnicky 2003)

Radio source is not associated with a visible star cluster

Hard X-ray Chandra point source coincident with radio source (Ott et al. 2005, Kobulnicky & Martin 2010)

Local peak in Paschen alpha and H alpha emission

Appears connected to a thin quasi-linear feature between two bright blobs

At center of ionized gas structure with a coherent velocity gradient (Henry et al. 2007)

Position consistent with dynamical center (from HI solid-body rotation (Kobulnicky et al. 1995))

The central source in Henize 2-10

Narrow-band imaging (ionized gas)

Paschen alpha line emission (1.87 microns)

H alpha line + continuum (0.66 microns)

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1 arcsec (44 pc)

Broad-band imaging (stars)

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ACS/HRC F814W (0.8 microns)

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The central source in Henize 2-10

Wide-Field Radio Image of the Galactic Center
$\lambda = 90$ cm
(Kassim, LaRosa, Lazio, & Hyman 1999)

Radio image of the Galactic Center
The central source in Henize 2-10

Radio image of the Galactic Center

24 pc x 9 pc beam
The central source in Henize 2-10

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Hubble Space Telescope

Very Large Array radio telescope

Chandra X-ray Observatory

Images from http://chandra.harvard.edu/press
Central region strongly emitting radio waves and energetic X-rays
The central source in Henize 2-10

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Active Galactic Nucleus

Narrow-band imaging (ionized gas)

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- H alpha line + continuum (0.66 microns)
- 3.5 cm contours

Broad-band imaging (stars)

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I arcsec (44 pc)
Ruling out alternative explanations
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Radio luminosity

\[ L_R (5 \text{ GHz}) \sim 7.4 \times 10^{35} \text{ erg s}^{-1} \]

Hard X-ray luminosity

\[ L_X (2-10 \text{ keV}) \sim 2.7 \times 10^{39} \text{ erg s}^{-1} \]

Very Large Array radio telescope

Chandra X-ray Observatory
Ruling out alternative explanations

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**Ratio of radio to X-ray luminosity:**

$$R_X = \nu L_\nu (5 \text{ GHz}) / L_X (2 - 10 \text{ keV})$$  
(Terashima & Wilson 2003)

*The central source in Henize 2-10:*

$$\log R_X \sim -3.6$$
Ruling out alternative explanations

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\log R_X \sim -3.6
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*Typical low-luminosity AGN:*
\[
\log R_X \sim -2.8 \text{ to } -3.8 \quad \text{(Ho 2008)}
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**The central source in Henize 2-10:**
log $R_X \sim -3.6$

**X-ray binaries:** too weak in the radio
log $R_X < -5.3$

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(Ho 2008)
An actively accreting massive black hole
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How massive?
An actively accreting massive black hole

How massive?

Merloni et al. 2003
An actively accreting massive black hole

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Merloni et al. 2003
An actively accreting massive black hole

How massive?

Merloni et al. 2003

The diagram shows a plot of log $L_X$ (2-10 keV) vs. log $L_R$ (5 GHz) for black holes. The plot distinguishes between supermassive black holes and stellar-mass black holes. Supermassive black holes are found in the upper right part of the plot, while stellar-mass black holes are generally located in the lower left part.
An actively accreting massive black hole

How massive?

Merloni et al. 2003

“fundamental plane of black hole activity”

\[ \log L_R = 0.60 \log L_X + 0.78 \log M + 7.33 \]
An actively accreting massive black hole

How massive?

Merloni et al. 2003

log \( L_X \) (2-10 keV) \( \text{erg s}^{-1} \)

log \( L_R \) (5 GHz) \( \text{erg s}^{-1} \)

0.60 \( \log L_X \) + 0.78 \( \log M \)

“fundamental plane of black hole activity”

log \( L_R = 0.60 \log L_X + 0.78 \log M + 7.33 \)

black hole in Henize 2-10 \( \log (M_{BH}/M_{\text{sun}}) = 6.3 \pm 1.1 \)
Supermassive black holes have typically been found in massive galaxies with bulges.

\[ M_{\text{BH}} \sim 1.4 \times 10^8 \, M_{\odot} \]  
(Bender et al. 2005)

\[ M_{\text{BH}} \sim 6.6 \times 10^9 \, M_{\odot} \]  
(Gebhardt et al. 2011)
Supermassive black holes have typically been found in massive galaxies with bulges

But not always...

\[ M_{BH} \sim 1.4 \times 10^8 M_{\text{sun}} \] (Bender et al. 2005)

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The Low-Mass Regime: Putting Henize 2-10 in context
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Filippenko & Ho (2003)
Peterson et al. (2005)

Kunth, Sargent & Bothun (1987)
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The Low-Mass Regime

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The Low-Mass Regime: Putting Henize 2-10 in context

Greene & Ho (2004, 2007)

174 broad-line AGN with $M_{BH} < 2 \times 10^6$ in SDSS DR4

Log black hole mass
The Low-Mass Regime: Putting Henize 2-10 in context

Greene & Ho (2004, 2007)

174 broad-line AGN with $M_{\text{BH}} < 2 \times 10^6$ in SDSS DR4

Log black hole mass

10
20
40
60
80
100

Number

≈ 93% extended disks (with pseudobulges)

≈ 7% spheroidals

Greene et al. (2008); Jiang et al. (2011)

Host Galaxies

- Low-luminosity galaxies, ~ 1 mag below $L^*$
- Well-defined optical nuclei
The Low-Mass Regime: Putting Henize 2-10 in context

Greene & Ho (2004, 2007)

174 broad-line AGN with $M_{BH} < 2 \times 10^6$ in SDSS DR4

- Type 2 counterparts to Greene & Ho sample
- 12 have stellar velocity dispersions $< 60 \text{ km s}^{-1}$ ($M_{BH} < 10^6$)

Greene & Ho (2004, 2007)

Barth et al. (2008)
Henize 2-10 is different

- Dwarf starburst galaxy with newly formed globular clusters
- Irregular morphology without a well-defined nucleus
Henize 2-10 is different

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- Irregular morphology without a well-defined nucleus
- **Massive black hole but no discernible bulge or nuclear star cluster**
Henize 2-10 is different

- Dwarf starburst galaxy with newly formed globular clusters
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- Massive black hole but no discernible bulge or nuclear star cluster

Early stage of galaxy and black hole evolution?
Local analogue to high-redshift black hole and galaxy growth?
The First Star-Forming Galaxies

- blue, compact galaxies 600-800 Myr after the Big Bang (Bouwens et al. 2010)
- intrinsic sizes ≤ 1 kpc (Oesch et al. 2010)
- masses ~ $10^9$-$10^{10}$ M$_{\odot}$ (Labbé et al. 2010)
- likely forming globular clusters
- likely host massive black holes (Treister et al. 2011)
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Henize 2-10 is our best available local analog of high-redshift black hole and galaxy growth
Main take-away points about Henize 2-10

• First example of a massive black hole in a local star-forming dwarf galaxy

• Nearby galaxy much like those in the earlier universe

• Best available analog of primordial black hole growth - opens up a new class of host galaxies to search for more

• No discernible bulge - black hole growth can precede the build-up of galaxy spheroids
Follow-up observations of Henize 2-10
Follow-up observations of Henize 2-10

Accepted Proposals

- **HST/STIS** - Kinematics and ionization conditions near AGN
  P.I. Reines (w/ Whittle, Johnson)

- **XMM-Newton** - X-ray follow-up
  P.I. Hickox (w/ Greene, Reines, Sivakoff, Johnson, Alexander)

- **VLBI with the Long Baseline Array** - High-resolution observations at 1.4 GHz
  P.I. Reines (w/ Deller, Johnson)
New (yesterday!) VLBI data

SNR in brightest super star cluster

1" (~44 pc)

AGN

Adam Deller
New (yesterday!) VLBI data

SNR in brightest super star cluster

AGN

HST + VLA

Map center: RA: 08 36 15.117, Dec: -26 24 34.070 (2000.0)
Map peak: 0.000616 Jy/beam
Contours %: 20 40 80
Beam FWHM: 131 x 38 (mas) at 83.1°

Adam Deller
Follow-up observations of Henize 2-10

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Submitted Proposals

• **EVLA** - Water maser observations  
  P.I. Reines (w/ Darling, Brogan, Johnson)

• **ALMA** - Dense molecular gas  
  P.I. Johnson (w/ Reines, Testi, Brogan, Vanzi, Wilner, Chen)
Searching for big black holes in little galaxies

Accepted Proposals

- Chandra + EVLA - mini survey of nearby star-forming dwarfs
  P.I. Reines (w/ Sivakoff, Condon)
Searching for big black holes in little galaxies

Accepted Proposals

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Starting to plan large-scale radio survey (w/ Jim Condon)
Discussion topics

1. Using the black hole fundamental plane to obtain masses

This is potentially a very powerful tool for obtaining black hole masses. How reliable is it (at low masses)? Would simultaneous X-ray and radio observations significantly reduce the scatter in the relationship?

2. The impact of metallicity on making “heavy” black hole seeds

Are extremely low metallicities required to make a massive seed? Can massive seeds form from direct collapse of enriched gas in the modern universe (e.g. Begelman & Shlosman 2009)?