Using HAWC+ to Find A Cold Quasar's Place in AGN Feedback

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Artist Conception Credit: NASA/ Daniel Rutter
SF SHUTDOWN DUE TO AGN

- **Merging galaxies**
  - gas-rich galaxies collide

- **Starburst**
  - dust-obscured star formation

- **Red quasar**
  - young jets
  - strong winds

- **Blue quasar**
  - evolved jets
  - weak winds

- **Early-type galaxy**
  - dormant galaxy

Gemini Observatory, GMOS-South, NSF, S. Munro
WHAT MAKES THIS DIFFICULT TO OBSERVE?

- AGN get many names for the same object.
- Identifying active AGN requires seeing the emission directly from the central engine.
- Optical emission lines can be used to map the broad line region.
- X-ray can be used to estimate the accretion rate.

AGN Unified Model
Urry & Padovani (1995)
The radiant energy from an actively accreting SMBH can heat and unbind the cold gas component of the host galaxy (e.g. Hopkins et al. 2006).

- However some targets remain star-forming while X-ray bright (e.g. Salome et al. 2015; Mahoro et al. 2017, Perna et al. 2018).

Goal: Understand how AGN shut down star-formation

- Find the rare objects where the cold gas remains while an AGN is active.
  - Far-infrared

- Find the rare objects where we can estimate how bright the central engine is (a.k.a., how much is the SMBH accreting material?)
  - X-ray, optical
STRIPES82X SURVEY

- A wide field X-ray survey (16.5 deg$^2$ XMM Newton coverage)
  - Designed to probe the high-z, high luminosity parameter space (LaMassa et al. 2013).

- Utilizes the Stripe 82 region of SDSS as a bedrock to guarantee optical/NIR photometry and limited spectroscopic coverage.

- Field found the first changing look quasar, which changed from unobscured to obscured (LaMassa 2015)

- Component of the Accretion History of AGN (AHA) survey.
Out of the X-ray-optical coverage, 15.6 deg$^2$ is also contiguously covered by the Herschel Space Observatory.
- Herschel Stripe82 Survey (HerS; Viero et al. 2014)

Observed using SPIRE at 250, 350, and 500 microns.

AHA team combined this coverage to form the multi-wavelength AHA survey catalog (Ananna et al. 2016)

https://www.herschel.caltech.edu/
Goal of AHA was to identify host characteristics of the brightest AGN.

When investigating the highest luminosity cases in Stripe82X, 4% of unobscured quasars were detected in the FIR.

Classified as: “Cold Quasars”
Cold quasars are a population of unobscured, IR-detected quasar.
- $L_x > 10^{44}$ ergs/s
- $S_{250} > 30$ mJy
- Combination of X-ray and IR detection selects for the narrow timeframe where the AGN has not cleared the gas.

Due to the 4% FIR detection rate of X-ray and optically selected quasars, we can loosely constrain their stage to $\sim 10^6$ yrs.

Span a wide range of host properties and epochs:
- $\text{SFR} \sim 200-1000$ M/yr
- $\log_{10}(M_*/M_{\odot}) \sim 10.5-11.2$
- $1 < z < \sim 2.5$
- Feature a compact bright source in SDSS color-composite images, determination of host properties requires looking to longer wavelengths.

- Broad optical emission lines confirm the unobscured classification.
Cold quasars satisfy NIR AGN classification, such as the WISE color criteria of Assef et al. (2018).

Generally redder and brighter than the unobscured sample (orange) or full Stripe82X sample (green).
Higher brightness in the longer wavelengths (W3 – 12 microns), sets them apart from the unobscured sample.

Interpreted as evidence for a lower optical depth or covering fraction.
SED fitting was performed using the WISE and Herschel photometry using a featureless AGN template (Kirkpatrick 2012) and submillimeter template (Pope 2008).

Derived SFRs from 300-1300 M/yr!

However, peak of FIR is loosely constrained.
Kirkpatrick et al. followed up on a sample of lower X-ray luminosity targets in Stripe82X.
- Included targets 0.5x the original X-ray cutoff
- PI: Kirkpatrick: 07-0096

Proposal targeted cold quasar candidates predicted to be bright in SOFIA HAWC+ FIR bands.
- Detection would constrain the FIR peak location
  → Dust Temperature and accurate SFR!

SOFIA HAWC+ chosen to enable a choice in imaging band to optimize the FIR peak detection for each target.
SOFIA FOLLOW UP

- Guest observing met with technical difficulties at first....

- Engine maintenance meant no flights while I was in California.
Reduced the images using the CRUSH pipeline in faint mode with help from the SOFIA team.

1 strong detection!

CQ 4479: 75.42 +/-14.2 mJy (SNR = 5.31) at 89um

$z = 0.405$

CQ4479

Cooke et al. (2020)
We use spectral energy distribution (SED) fitting codes with stellar, dust, and AGN components to determine the energy output from each one.

**CIGALE for model customization, SED3FIT for dust temp.**

Cooke et al. (2020)
SOFIA’S CRITICAL ROLE

Cooke et al. (2020)
CQ 4479 IS STARBURSTING!

\[ \log_{10}(SFR) \left[ M_\odot \text{ yr}^{-1} \right] \]

\[ \log_{10}(M_*) \left[ M_\odot \right] \]

CQ 4479
Kirkpatrick et al. (2020, submitted)
Schreiber et al. (2015) z = 1.620
Schreiber et al. (2015) z = 0.405

Cooke et al. (2020)
SDSS DR16 spectra exhibit broad MgII, Hβ, and Hα emission lines consistent with Type-1 AGN.
Sloan Digital Sky Survey provides spectra for optical emission lines [OIII], Hα.

We normalize and fit each line with a narrow and broad Gaussian component to find FWHM and flux from the broad component.
- Used to estimate $M_{\text{SMBH}}$
- $M_{\text{sol}}$ / yr [O III]: 0.30

The [O III] line is asymmetric, requiring a second Gaussian component.
- -202 km/s from systematic
The X-ray luminosity directly traces the regions of the accretion disk closest to the central engine.

- \( L(2-10 \text{ keV}) = 3.4 \{+0.15\} \{-0.19\} \times 10^{43} \text{ erg s}^{-1} \)

Use bolometric luminosity derived from [OIII] and X-ray emission from XMM-Newton to estimate accretion rate.

- \( M_{\text{sol}} / \text{yr [X-ray]}: 0.11 \)
- \( M_{\text{sol}} / \text{yr [OIII]}: 0.30 \)

(e.g., Shakura & Sunyaev 1973)
We find that cold quasars behave similarly to previously observed samples of Herschel-detected broad-line AGN at $z < 1$ (Sun+2015).

Stellar mass and black hole mass grow at different scales, but at correlated rates that teach us the SMBH `knows' of the gas available in the galaxy.

SMBH and stellar component are growing in lock-step, indicating this is truly an early stage where SFR is not shutting down.
WHAT ARE COLD QUASARS?

- Luminous B-band
- Luminous X-ray
- Medium winds

**Merging galaxies**
- gas-rich galaxies collide

**Starburst**
- dust-obscured star formation

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CQ 4479
- Luminous FIR
- Ongoing star formation
- Medium winds
Select targets from Stripe82X that have optical detections but no counterpart detected at 250 microns.

- 2785 sources

Stack the FIR image at each location for targets in bins of X-ray luminosity.

- X-ray chosen to characterize the state of the AGN, and whatever the stacks result in teach us of the median star-forming behavior of the sample.
Stacking of unobscured quasars in Stripe82X that have not been detected in the FIR show a population that is growing both components slower than cold quasars.

Median SEDs of the stacked FIR targets exhibit lower SFR and $L_{\text{bol}}$.

Being below the main sequence is commonly associated with post-starburst, quiescent galaxies.
FUTURE FOLLOW-UPS

- HST-resolution optical images are highly desired to determine the state of the host galaxy.

- Due to the improved SFRs, more SOFIA measurements will continue to be applied for.

- Currently discussing the availability and feasibility of radio observations to determine the kinematics of the host gas.

- Long-term: Roman surveys will provide enormous optical imaging catalogs along fields with FIR coverage, enabling the examination of far more cold quasars.
CONCLUSIONS

- Cold quasars represent a rare phase between red and blue quasars where we can observe the co-evolution of an active supermassive black hole and ongoing star-formation.

- SOFIA is the only facility that can deliver new observations to constrain the gas temperature and SFR without contamination from the AGN.
Thank you!

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NEED TO GET YOUR STUDENTS UP TO SPEED?

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- arXiv: 2006.12566

Cooke et al. (2020, arxiv)