Astro2020 Science White Paper

Extremely obscured galaxy nuclei – hidden AGNs and extreme starbursts

Thematic Areas: Galaxy Evolution

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Abstract:

Rapid evolution occurs when galaxies and their nuclei are enshrouded in dust and gas. Molecular gas fuels the embedded luminosities and is a primary factor behind enhanced star formation rates and black hole accretion (=Active Galactic Nucleus, AGN).
A full census of obscured stellar and black hole growth requires studying the extremely obscured activity (the Compact Obscured Nuclei - CONs) that has recently been uncovered using submm facilities. Properly interpreting these observations requires advances in the radio, mm/submm, far-infrared and X-ray facilities than can peer through the obscuration.

Local, luminous and ultraluminous infrared galaxies[1] (U/LIRGs) are mainly powered by extreme bursts of star formation and/or Active Galactic Nuclei (AGNs) (accreting SMBHs) in their centres. *U/LIRGs are the closest examples of rapid evolution in massive galaxies*, often the result of mergers or interactions between gas-rich galaxies where enormous amounts of interstellar matter (ISM) are funnelled into the remnant centres (e.g. Sanders & Mirabel 1996). The infrared luminosity of U/LIRGs stems from emission absorbed and re-emitted by dust enshrouding the starburst/AGN activity. But less spectacular, lower luminosity galaxies may also have embedded nuclei hiding a rapidly growing SMBH and/or stellar population (e.g. Hickox & Alexander 2018, HA18). In both situations, molecular gas fuels the embedded luminosities and is a primary factor behind enhanced star formation rates and nuclear activity.

Studying the accretion and growth of SMBHs is essential for our understanding of how they coevolve with their host galaxies[2] (e.g. Ho 2004, Chen+13). AGN population synthesis models suggest an average ratio of obscured to unobscured AGN of about 3:1 in the local Universe. The fraction of obscured sources increases even further towards lower luminosities (Goulding+09). Important studies of obscured AGN and starburst activity are carried out at mid-IR wavelengths using high-excitation mid-IR lines (e.g. [Ne V] as an AGN diagnostic Genzel+98) and silicate absorption to study obscuration. The *ISO* and *Spitzer* space telescopes have been fundamental to the mid-IR charting of embedded evolution (e.g. Sturm+02, Farrah+07, Petric+11, Stierwalt+13+14). X-rays are also essential probes of obscured AGN[3]. The emission originates from the close environs of the SMBH and can penetrate layers of gas and dust to reveal the accretion state (see e.g. HA18). The spectral shape of the transmitted and reflected X-rays can provide key clues to the geometry and physical conditions of the obscuring material (Balkovich+18). However, there is growing evidence of a population of AGNs that are so deeply embedded that they are also obscured in the mid-IR and observable X-rays (e.g. Alexander 11, Lusso+13). In the Compton thick (CT) regime, one can only study the much fainter X-rays that are reflected or scattered around the absorber (e.g., Georgantopoulos+13).

Recent studies with mm/submm telescopes such as *NOEMA*, *SMA*, and *ALMA* and far-infrared (FIR) space telescopes such as *Herschel* have revealed U/LIRGs that host extremely Compact Obscured Nuclei (CONs). These nuclei tend to be Compton thick with extreme H_2 column densities $N(H_2) >> 10^{24}$ cm^{-2} (e.g. Sakamoto+08+10+13+17; Aalto+15+19; Gonzalez-Alfonso+12, Costagliola+13, Falstad+15, Wilson+14, Rangwala+15, Martin+16, Scoville+17, Barcos-Munos+18). In extreme cases, $N(H_2)$ can even exceed 10^{26} cm^{-2}. CONs occur during phases of rapid evolution. They have distinctive submm and FIR characteristics, and there is now mounting evidence that they may harbour rapidly growing SMBHs (e.g. Aalto+19). *Studies of CONs are essential for understanding AGN duty cycles, feedback, and the links between obscuration and SMBH fueling.*

CONs are produced by dense molecular gas that can also support star formation. However, due to the high degrees of obscuration, the levels of star forming activity and its connections to the SMBH are not known. If young stars are major power sources, then the initial mass is likely enriched in high mass stars and the stellar feedback and element production could be enhanced. As the stars cannot be directly observed, methods using dust-penetrating, long wavelength signatures,

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[1] ($L_{IR} = L_{bol} = 10^{11}$-$10^{12}$ $L_\odot$)

[2] See also Astro2020 white paper by A. Pope et al. on *Simultaneous Measurements of Star formation and Supermassive Black Hole Growth in Galaxies over Cosmic Time*.

[3] See also Astro2020 white paper by Civano et al. on *Cosmic Evolution of Supermassive Black Hol*es.

such as FIR/submm/radio measurements of elemental abundances or radio detection of supernovae, are options for exploring this critical aspect of rapidly evolving nuclei.

2. Star formation and AGN activity: FIR and submm diagnostic lines and continuum

Where are the most dust-enshrouded growing supermassive black holes (SMBHs) and extreme bursts of star formation in the nearby Universe?

2.1. Molecular diagnostic lines of buried luminosity density and ionization

In the most extremely embedded regions, we can use molecules as proxies of the buried luminosity density. Through bending and vibrational modes, molecules may become excited by e.g. short-wavelength IR emission from dust – severely attenuated at its intrinsic wavelength, but revealed via the longer wavelength molecular line emission (Fig. 1).

Highly excited lines of H_2O (212 and 71 μm) and OH (65 μm) have proven efficient in identifying CONs (e.g. Gonzalez-Alfonso+12+14, Falstad+15+17). The line ratio of two water lines 7_{17}-6_{06}/4_{23}-3_{12} is a good test of the temperatures of the exciting FIR dust continuum. This effect becomes stronger for large columns (Gonzalez-Alfonso+14, Falstad+15). Rotational-vibrational lines of HCN (20-1000 μm) can be used to find hidden, high-surface brightness ($\Sigma > 5 \times 10^{13}$ $L_\odot$ kpc^{-2}) mid- and near-IR continuum. They require large H_2 columns ($>5 \times 10^{23}$ cm^{-2}) to be excited (e.g. Aalto+15). The combination of these is essential to separate photon- from non-photon driven processes. The vibrational lines allow us to reconstruct the real IR spectral energy distribution (SED) buried behind the dust and gas (e.g. Aalto+15+19). Adding molecular ions such as H_3O^+, H_2O^+, and OH^+ provide ionization rates and cosmic ray energy densities, further addressing the nature of the enshrouded source. High-*J* lines of CO reveal the temperature and density structure of the buried activity (e.g. van der Werf+10, Gonzales-Alfonso+12, Greve+14, Rosenberg+15).

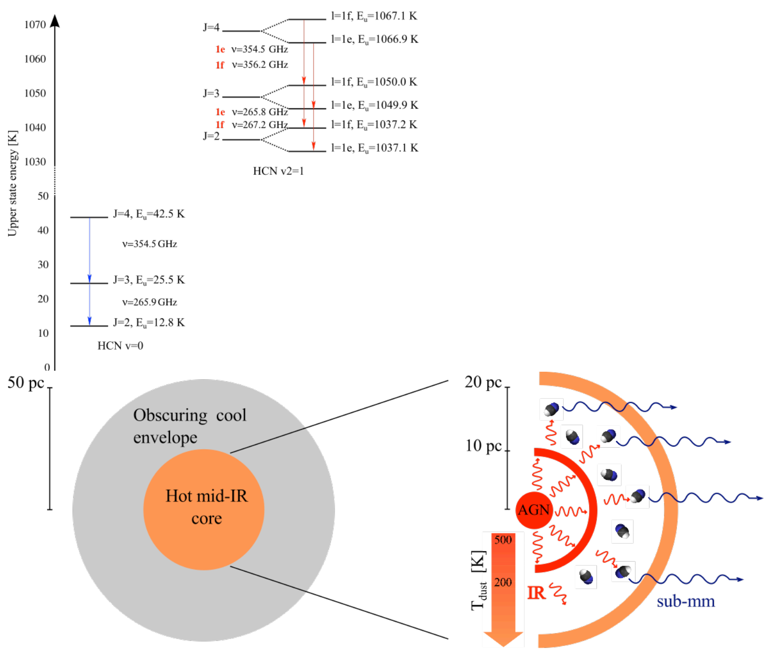

Fig.1 Top: Energy diagram of HCN in the rotational ground state and the vibrationally excited ladder. Transitions in the mm and submm that can be observed with ALMA are shown with arrows. Bottom: Sketch illustrating a buried mid-IR core and how the submm emission of the vibrational HCN line can penetrate the surrounding dust. (Aalto+15, cartoon designed by F. Costagliola)

A dust SED is an important tool to study the relative contributions of AGN and starburst activity in a galaxy (Mullaney+11). For extremely obscured objects, caution when using galaxy-integrated SEDs is however advised. The SED may be dominated by extended star formation that is masking a CON and a vigorously growing SMBH (its mid-IR continuum may be attenuated by orders of magnitude; Aalto+19). Applying the above diagnostic lines will help correct the SED for the missing buried component.

2.2. Metallicity and stellar nucleosynthesis

How is nuclear star formation connected to the growth of the SMBH, and is the IMF of nuclear embedded star formation different from that of more normal star formation?

2.2.1 FIR and submm isotopic lines

A novel approach in the study of the evolution of AGN and starburst activity, and how it links to the transformation of the host galaxy, is to observe and model molecular species and isotopic tracers of nuclear enrichment such as ^{18}O, ^{13}C, and ^{15}N. In the Far-IR, species such as $H_2{}^{18}O$ and ^{18}OH are key tracers of the enrichment by massive stars. Observations and simulations reveal that ^{18}O is primarily produced in massive stars and brought out in supernova explosions – i.e. after 3 Myr. These abundances, together with, for example, ^{13}C which is produced only in low mass stars, can be used both to test for IMF as well as the time evolution of a burst. Enhancements of ^{18}O in Seyfert 1 nuclei suggest very recent massive star formation close in time to the AGN activity (e.g. Gonzalez-Alfonso+12, Sliwa+17). How these enhancements are related to AGN luminosity and host galaxy evolution is not well understood. Recent studies reveal that large-scale inflows of gas and dust in e.g. minor mergers can alter the metallicity and isotopic ratios of the nuclear gas. (e.g. Sakamoto+09, Fischer+10, Gonzalez-Alfonso+12, Henkel+15, Falstad+15, König+16). These inflows are an important process, linking nuclear growth to that of the host galaxy evolution.

2.2.2 FIR Fine structure lines

Galaxies exhibit a wide range in metallicities. A strong link between metallicity and stellar mass exists (e.g. Mannucci+10), and in recent years, this mass-metallicity relation has been expanded into a three-dimensional relation, adding the star formation rate (SFR) as third parameter (e.g. Dayal+13). How is this fundamental metallicity relation generated and what is the role of extremely obscured star formation? To answer these questions, we need access to diagnostics of the gas-phase metallicity that can probe dusty regions. Combining far-infrared fine structure lines Pereira-Santaella+17 and Rigopoulou+18 developed new gas phase metallicity diagnostics suitable for dusty galaxies. Fine structure lines such as [OIII]52, [OIII]88 and [NIII]57 and [NeII]122 μm are reliable indicators of the metal content.

3 Obscuration and feeding

How are the accretion rates of SMBHs linked to size, structure and degree of obscuration? What are the connections to nuclear dynamics such as inflow?

3.1 CONs and X-ray CT AGNs

Existing studies suggest that CONs have CT obscuration on scales of tens of pc (Sakamoto+13, Aalto+15+19). In contrast, the obscuration in many X-ray selected CT AGNs (XCTs) is believed to occur on scales one order of magnitude lower (see e.g., HA18). CONs may therefore be galaxy nuclei in a very different stage of evolution (e.g. SMBHs in a high accretion rate) than XCTs (see e.g. Ricci+17). In addition, the column densities we find for CONs are also extremely large - which makes direct X-ray detections extremely difficult - in particular since there is intervening material on scales beyond the pc-scale nuclear distribution, potentially obscuring any scattered or reflected nuclear emission. To understand how these two populations of obscured galaxy nuclei are related, extensive and sensitive statistical studies are required. Are CONs an extension of the most obscured XCT population – or do they represent an entirely different phase of obscured evolution?

3.2 High resolution: ALMA and radio facilities

With an interferometer, IR and FIR surface brightness can be resolved with pc-scale resolution in nearby galaxies. Effects of absorption and emission can be separated and nuclear dynamics in the form of rotation, inflows and outflows studied in detail. Recently the LIRG CON IC860 has been probed at 20 milli-arcsecond (5 pc) resolution revealing a compact (*r*=9 pc) dusty nucleus of enormous H_2 column density ($N(H_2)=5 \times 10^{26}$ cm^{-2}) and a hidden mid-IR surface brightness Σ(mid-IR)>2×10^{15} $L_\odot$ kpc^{-2}. The nuclear activity is fed by a massive inflow of molecular gas (Aalto+19a). Similar column densities have been found in the major merger ULIRG Arp220 (e.g. Scoville+17, Sakamoto+17, Barcos-Munos+15+18) which also has a fast (850 kms^{-1}) and collimated molecular outflow (Sakamoto+09, Rangwala+15, Tunnard+15, Sakamoto+17, Barcos-Munos+18, Wheeler et al in prep).

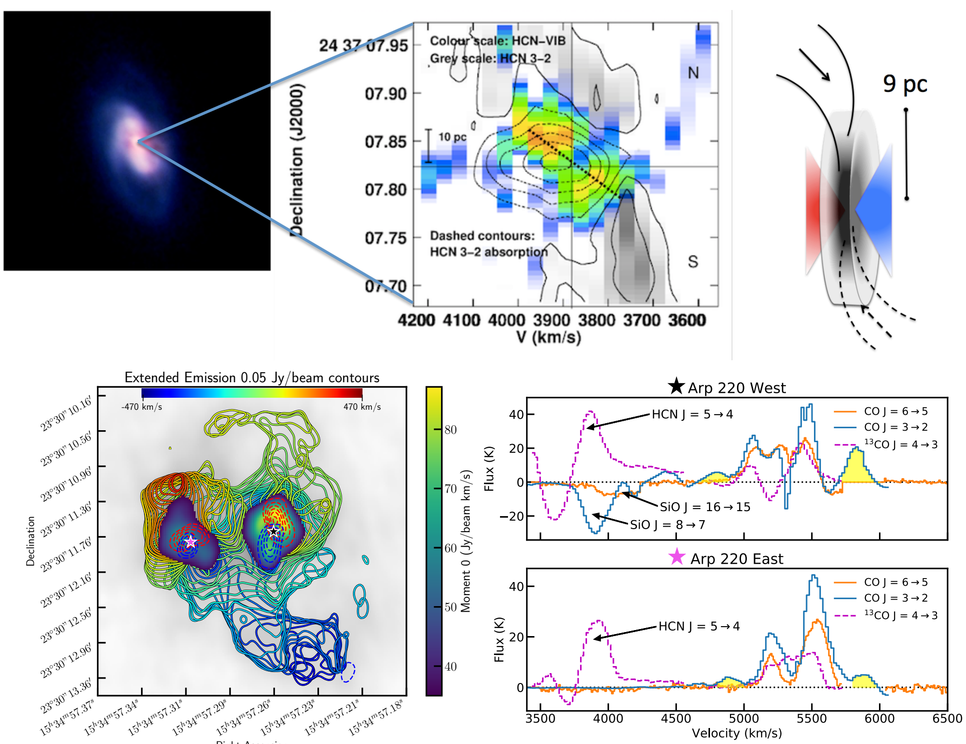

Fig. 2 Upper left: Nordic Optical Telescope image of the LIRG IC860. Upper centre: position velocity diagram of HCN 3-2 (grayscale) and vibrationally excited HCN (colour) where the vibrational line is seen in emission in contrast to the absorbed ground-state HCN. Upper right: Cartoon of the inflow/outflow of the inner 10 pc of IC860 (Aalto+19)

Fig. 2 Lower left: Arp220 color image of CO 3-2 emission. Nuclear high velocity outflowing gas is shown in dashed red and blue contours. Lower right: continuum subtracted CO line profiles from two nuclei. Absorption features at the centers of the eastern and western nuclei and the extremely bright HCN 5 -4 emission. High velocity gas outflow in CO 3-2 is highlighted in yellow (Wheeler et al. in prep)

Auxiliary multi-frequency radio observations (e.g. with JVLA, eMerlin, and Very Long Baseline Interferometry, VLBI) are needed for the high-resolution study of obscured star formation and AGNs and are necessary to calibrate how thermal radio emission may be suppressed by high column-density environments (e.g. Barcos-Munos+15).

4. Key observational facilities

To reveal the nature and evolution of the most deeply buried activity requires a sensitive FIR telescope with sufficient resolution to single out the nuclear region. With a telescope such as the *Origins Space telescope (OST),* we can reach unique tracers of buried activity and survey large samples of galaxies in the nearby universe. With a sensitivity 100 times that of the *Herschel* space telescope, OST will revolutionize molecular spectroscopy as a tool to probe the most deeply obscured phase of galaxy evolution. The FIR adds new key tracers of deeply obscured nuclear growth to the important diagnostic features in the mid-IR where the upcoming *JWST* space telescope will carry out transformational new science. The FIR tracers dig deeper into the dust enabling us to probe star formation and black-hole accretion in the most embedded objects.

High-resolution long-wavelength studies are important for detailed, extinction-free, studies of obscured activity. With the new mm/submm facility ALMA, the gas, dust and luminosity density of obscured galaxy nuclei are probed on pc-scales (milli-arcseconds). Future radio interferometers such as the ngVLA and/or the Square Kilometer Array (SKA) provide complementary, sensitive studies of star formation and AGN activity. High-energy tracers, such as X-rays, are key to our understanding of embedded growth. To be able to detect the accretion signatures of extreme obscuration requires new X-ray facilities with significantly improved sensitivity as well as high spatial and spectral resolution, such as the planned X-ray missions and concepts include *XRISM*, *Athena*, *Lynx*, *STROBE-X*, *AXIS*, and *HEX-P*.

Understanding the evolution of galaxies and galaxy nuclei requires studying the heavily obscured activity that has recently been uncovered using submm facilities. Properly interpreting these observations requires advances in the radio, mm/submm, far-infrared and X-ray facilities than can peer through the obscuration.

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