Physical Conditions and Chemistry of Molecular Gas in Galactic Centres

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Outline

• Physical conditions and chemistry
• Dusty nuclei
  • Vibrational lines – peeking behind the veil of dust
• Starburst nuclei
• AGNs
Driving the gas to the center

- Spiral arms
  - Flocculent
  - Grand design
- Bars
  - Strong/weak
  - Nested
- Interacting galaxies
  - Polar rings, dust lanes counterrotating and infalling gas
  - Tidal gas
  - "Overlap regions"

...and it collects in: disks, rings, mini-bars, Compact Obscured Nuclei (CONs)

...Feeding AGNs, starbursts and driving outflows and winds

Grand design molecular spiral in M51
Aalto et al 1999

Molecular bar in NGC1530
Reynaud et al 1999

Minor merger NGC1614
Olsson et al 2010

600 pc starbursting molecular ring
(König et al 2013)
Why astrochemistry?

• Its there! ...(and we are creatures driven by curiosity)
• We can use it as a tool to study galaxy evolution - in particular in dust-obscured objects:
  – Starburst and AGN (Active Galactic Nuclei) evolution
  – Starburst and AGN classification
  – Feedback mechanisms
  – Impact of shock, outflows, turbulence

HST image of Arp220 inner region

The dusty cores of the Ultraluminous infrared galaxy Arp220. $A_V>1000$ in both nuclei

SMA spectral scan (Martin et al 2011)
Astrochemistry as a diagnostic tool

A few standard scenarios:

- **X-ray dominated region (XDR)** – large bulk temperatures > 100 K (e.g. Maloney et al 96; Lepp & Dalgarno 96; Meijerink and Spaans 05)
- **Photon dominated region (PDR)** – large surface temperatures 300-1000 K – moderate bulk temperatures 20-50 K (e.g. Hollenbach & Tielens 97)
- **Cosmic ray dominated region (CDR)** (e.g. Suchkov et al 93; Meijerink et al 11)
- **Dense shielded regions** – dusty hot core-like chemistry (IR pumping), 50-300 K (see e.g. work by Viti, Millar)
- **Mechanically dominated region** – shock-chemistry (e.g. Viti et al 11; Kazandjian et al 11)

Main question: What are the key spectral signatures of the above scenarios?
Extragalactic molecules

Table 5. Census of extragalactic molecular species and isotopologues detected

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<th>4 atoms</th>
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From: Martin et al 2011
Popular diagnostic lines

Physical conditions

**Gas density**
Low-J CO to trace low density gas $n > 10^2$ cm$^{-3}$

High dipole moment molecules such as HCN to trace dense gas $n > 10^4$ cm$^{-3}$

**Gas temperature**
- NH$_3$, H$_2$CO
- CO ladder

**Isotopomers**
- e.g. CO/$^{13}$CO
  - tracer of optical depth and ISM/cloud structure, stellar processing

This only works when molecules excited by collisions – caveat for centers of galaxies
Rough trends

- CO/HCN ratio decreasing towards galaxy centers
  - Increasing average gas densities
  - Higher pressures

- CO/13CO ratio increasing towards galaxy centers
  - Elevated gas temperatures
  - Diffuse molecular gas
"Raisin roll" molecular medium?

Dense cores/clumps
10^5 cm^{-3}
traced by HCN, CS, HCO^+, HNC etc

Low density
10^2 cm^{-3}
diffuse molecular gas
traced by low-J CO

Molecular mass in dense clumps

Volume dominated by diffuse gas

Bright HCN 1-0 – subthermally excited CO and large CO/^{13}CO 1-0 ratios

High pressure ISM with low columns of HI
Popular diagnostic lines

Astrochemistry

Molecular ions:
• HCO$^+$
• H$_3$O$^+$

Isomers:
• HNC
  – Elevated HNC/HCN ratios in cold gas, elevated ratios in XDRs, PDRs. Shocks remove HNC.
  – (e.g. Schilke et al 92; Aalto et al 2001; Aalto et al 2007b; Baan et al 2010)

Carbon chains
• HC$_3$N
  – Elevated HC$_3$N/HCN ratios in dense, shielded gas. Tracing IR field? (see later slides). (e.g. Aalto et al 2007a; Costagliola and Aalto 2010)

Radicals
• CN
  – Enhanced in XDRs, PDRs (e.g. Aalto et al 2001; Baan et al 2010; Meijerink and Spaans 2005)

Shock tracers
• SiO, H$_2$O
  – Enhanced in strong shocks – for SiO grain sputtering is required.
• HNCO and CH$_3$OH, NH$_3$
  – Enhanced in spiral and bar shocks

HCN/HCO$^+$ plot of Kohno et al – is it an AGN tracer?
Global line ratio trends

No strong trends in the brightest tracers.

- In general: HNC 1-0 luminosity is anticorrelated with HCO$^+$ 1-0
- $C_2H$ is everywhere...

Stronger trends for weaker lines – e.g. $HC_3N$:

- $HC_3N$ luminous galaxies (circles) always appear for HCO$^+$ faint and HNC luminous galaxies

All $HC_3N$ luminous galaxies have significant mid-IR silicate absorption features obscured galaxies young activity?

Strategy:
- Use spectral scans to find weaker lines and identify dominant chemistry.
- Observe at higher resolution.
What is buried behind the veil of dust?

HOT CORES
Compact Obscured Nuclei (CONs): Extreme, nuclear molecular disks.

Arp 220: SMA 860 μm obs.

NGC4418 SMA 1 mm & Merlin 1.4 GHz continuum

Costagliola et al 2013, Sakamoto et al 2013

NGC4418 is an interacting Sa LIRG with two orders of magnitude lower luminosity than Arp220 – but shows a similar compact obscured nucleus

Arp220 is a system of two merging gas-rich disk galaxies.
It is not known if its enormous IR luminosity $10^{12}$ L$_{\odot}$ is driven by star formation or accreting black holes.

Compton thick, hot dusty cores:

- Nuclear column densities $> 10^{24}$ cm$^{-2}$,
- gas surface densities $> 10^4$ $M_{\odot}$ pc$^{-2}$

Rotating disks & warm gas, confirmed

(Sakamoto et al '06)
Winds of change - a molecular outflow in the most extreme FIR-excess, radio-quiet galaxy

NGC1377: Small, lenticular galaxy
$L_{\text{FIR}}=5\times10^9 \, \text{L}_\odot$
Excess FIR emission with $q>3.9$ – off
FIR-Radio correlation by factor $>37$

The most extreme silicate absorption galaxy to date (Spoon et al 2007).
No $P\alpha$, $Br\,\gamma$ – Faint $H\alpha$, $[N\,\text{II}]$ and $[Ne\,\text{II}]$ lines, Faint PAH (Roussel et al 2003, 2006)

Featureless morphology apart from southern minor axis dust structure
Post starburst/LINER optical characteristics

What is powering the compact IR luminosity - Obscured AGN or nascent starburst?
SMA CO and $^{13}$CO 2-1 observations

Line wings (top panel) and disk rotation (lower panel) reveal a disk-outflow system

Nondetection of $^{18}$O consistent with lack of processed gas?

(Aalto et al 2012)
• Molecular mass: $1-6 \times 10^7 \text{ M}_\odot$
• Extent: 400 pc
• Opening angle: $60^\circ – 80^\circ$
• Age(?): 1.4 Myr
• Outflow velocity: 150 - 200 km s$^{-1}$
• $dM/dt$: 8–38 M$\odot$ yr$^{-1}$
• Molecular core of $N(\text{H}_2)>10^{23}$ cm$^{-2}$

Outflow appears to accelerate to maximum speed already at nucleus
NGC4418
345, 230 GHz SMA observations + MERLIN HI

- Submm continuum at 860 μm emerges from a <0. "1 (~20 pc) core at the nucleus. The 1.4 GHz continuum has a source size of 0.5."
- Total luminosity of the 20 pc core is approx $10^{11.0} \, \text{L}_\odot$ - the bulk of the total luminosity of NGC4418.
- $T_B(860 \, \mu\text{m}) = 120-210 \, \text{K}$, $\tau(860 \, \mu\text{m}) = 1$ (i.e., $N_H > 10^{25} \, \text{cm}^{-2}$).

Sakamoto et al 2013, Costagliola et al 2013
Lines include: CO 3-2, 2-1, HCN 4-3 $v=0$, $v_2=1$, HCO+ 4-3, HC$_3$N (ro+vib), C$^3$S, N$_2$H$^+$, CS 7-6, HNC (ro + vib).
VLBI 1.4 GHz structures found outside of submm continuum (Varenius et al 2013)
Inner region of NGC4418?

- 1.4 GHz synchrotron from SN and SNRs
- Optically thick dust/molecular core of T=200-500 K, D<20 pc
- Molecular disk T=50-100 K, D=100 pc
• How common are optically thick dust/molecular cores? What are their impact on our understanding of AGN and starburst evolution?
  – Half of the AGN population may be deeply buried.
• How can we study them?
  – Hard X-rays? Possibly – but they may be too thick?
  – High resolution ALMA observations
    • Continuum cores
    • vibrationally excited lines to probe inside optically thick dust veil
VIBRATIONALLY EXCITED MOLECULES
IR pumping of HC$_3$N, HCN in LIRGs and ULIRGs


An example: NGC4418

AGN or nascent starburst?

• Bright high-$J$ lines detected with APEX, JCMT, IRAM 30m, SMA
• Intense vibrational lines, $v_6$ $v_7$

HC$_3$N, HCN, HNC respond to intense radiation field of buried nucleus - revealing hot, compact 300 - 500 K component.
Vibrationally excited HCN

Combining vibrational lines from IR-pumped species let us probe the inner few pc of dusty active galaxies – beyond the optically thick atmosphere of dust. We can address issues on:
- the nature of the buried source
- if the source can cause a radiation pressure driven outflow

HCN 3-2 \( v_2 = 1 \) in Mrk231

HCN \( T_{\text{vib}} = 300 \) – 500 K

= tracing dust component in inner 20 pc of Mrk231

we can use the 14 micron optical depth to determine the possibility of radiation pressure as a driving force of the flow.

(Aalto, Muller, Garcia-Burillo, Winters, Gonzalez-Alfonso, Neri, Henkel, van der Werf in prep)
Vibrational dynamics – tracing the nuclear warped disk

Almost face on stellar disk

Inner 0.″2 – 0.″3 warped disk (Davies et al 2004). Inner 0.″1 nuclear OH torus or disk (Klöckner et al 2003)
Amplified IR-pumped HNC in Arp220W

Narrow, bright emission feature where CO and HCO+ show absorption

SMA Interferometric detection of HNC weak maser in ULIRG Arp220 (Aalto et al. 2009)
Potentially pumped by 21.5 micron continuum – amplifying background submm continuum.

Reflects unusual and extreme conditions in ULIRG, LIRG nuclei

mid-IR pumping of HNC via bending mode occurs at 21.5 mm at 669 K – pumping starts to become effective at TB(IR) = 50 K (Aalto et al. 2007)
**ALMA NGC4418 spectral scan**

**Science goals:**
- Obtaining a template chemistry/excitation for LIRGs
- Use IR pumped molecules to probe nature of buried nucleus
- Physical conditions in the gas
- Search for signs of outflows

**Collaborators:**
European MasTER network (PI: Costagliola)
K. Sakamoto – ASIAA, Taiwan
A. Evans – U. of Virginia, USA

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8 minutes on-source per tuning!
SPECTRAL SCANS
...and here is almost the whole Band 3:
SMA 1mm spectral scan of the enshrouded ULIRG Arp220

The dusty cores of the ULIRG Arp220. $A_v > 1000$ in both nuclei...

SMA 1mm spectral scan of Arp220 shows the stunning richness of the molecular spectrum. utilizing the broadband backend of the SMA. (Martin et al 2011). The survey covered the 40 GHz frequency range between 202 and 242 GHz of the 1.3 mm atmospheric window.

The Arp220 scan shows 73 features identified from 15 molecular species and 6 isotopologues. Note the multitude of $\text{HC}_3\text{N}$ lines – both vibrational and rotational.

28% of the total measured flux is due to the molecular line contribution, with CO only contributing 9% to the overall flux.

Fig. 6.— Detailed view of the spectral line survey. Spectral resolution of the observed data is smoothed to 20.5 MHz ($25 - 30 \text{ km s}^{-1}$ across the covered range). The LTE model of the identified molecular species is represented in thick continuous line. Identified molecular features are indicated.

Accepted cycle 1 band 6 programme for Arp220 spectral scan
Tracking evolution

STARBURSTS
Starburst have been the evident target for large molecular line searches

First unbiased mm line surveys of the two brightest extragalactic sources

**IRAM 30m**
2mm Atm window ~46 GHz (129–175 GHz)  
+ 19 GHz (241–260 GHz) in M82

2 x 1 GHz FB

111 lines / 25 species

(Martin et al. 2006)

72 lines / 18 species

(Aladro et al. 2011)
Nobeyama: NGC 1068, NGC 253, and IC 342

- Completed: 85~116 GHz
- Sensitivity: rms ~ typically 1-4 mK for NGC 1068, 2-13 mK for NGC 253, and 1-2 mK for IC 342

Chemistry in starbursts – IC 342, Maffei 2
(Meier and Turner 2006, 2012)

CH$_3$OH & HNCO follow the molecular bar arms, especially the bar ends.
In Maffei 2, C$_2$H prefers the starburst region, but is more extended and there is an outflow.
In IC342, C$_2$H is found near the nuclear star cluster and NOT the current star formation.

HCN, HNC, HCO+ & 3mm continuum tightly correlated, indicating a close connection to star formation.

HNCO, CH$_3$OH, and SiO are tightly correlated with each other and anti-correlated with the star formation molecules.
Impact on environment

AGNS
PdBI map of CO 1-0 and SiO 2-1

Top: SiO integrated intensity map overlaid on the CO(1-0) integrated intensity map. Lower: Zoomed view on the inner 12" around the AGN (identified by the cross). (Garcia-Burillo et al 2010)
Emission detected throughout the disk: central CND bar, spiral arms and SB ring - and interarm regions. (Noise 1.8 mJy, dynamic range = 1500. Spatial resolution 0."5x0."4 (35x28 pc)

Emission detected in CND in off-centered closed ring.
Velocity field shows overall rotation of disk (PA 90 deg). Non circular motions in spiral arms and bar. PA rotates to 0 degrees in central region.
pV plots along PA=90, CO 6-5 contours, HCO+ 4-3 colour. Note HCO+ peaking on AGN

HCN/HCN+ ratio in CND

HCN 4-3 in the CND

HCN/HCO+ 4-3, CO 6-5
**The Seyfert 1**

**NGC 1097**
An ALMA and ATCA Molecular Line Survey toward Centaurus A

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Abstract

We present Atacama Large Millimeter/submillimeter Array and Australia Telescope Compact Array data of molecular absorption lines toward the bright central core of Centaurus A. The line of sight crosses the prominent dust lane and continues through the disk and eventually through gas that may be very close to the central supermassive black hole. The goal of our survey is to determine the physical conditions of the gas via analyses of molecular line tracers including molecular abundances and excitation conditions that are sensitive to changes in temperature, density, ionization, and shocks. This study allows us to derive the physical conditions of each absorption line complex and allows us to define the main process shaping its environment. We present a first analysis of our data in the 13, 7, 5, and 1mm wavebands.

Left: We observed Centaurus A with ALMA in 20 different spectral lines at bands 3 (3mm) and 4 (1mm). Our main science goal focuses on the molecular absorption profiles against the bright supermassive black hole in the central region. The line of sight passes through the dust lane in the outer parts of the giant elliptical, further through the warped disk into the influence zone of the supermassive black hole. This is reflected by the different absorption components. The HCO+(1-0) shows a broad component that is associated with the overall profile best; very narrow, deep absorption features of the system exhibit a high density component at higher velocities that exhibits some narrow spikes. The broad component may indicate outflow or inflow from/to the black hole. The molecular spectra trace the chemistry and physical conditions in each component. Surprisingly, the C2H spectrum, which is sensitive to the higher-level component, and might be associated with this particular gas phase, shows prominent absorption features such as CH3CN, CN, and CN appearing to be much more abundant than CH3CN at the level of the H2O spectrum. Neodymium-deuterated isotopologues such as CH3CN and CN are observed to be much more abundant than CH3CN, which is centered in the brightest hyperfine substructure line. The HCO+ traces weak shocks and ISM in every spectral component.

Below: The large, fainter outer radio lobes (Maciej et al., 2011).

Left: Corresponding spectra of Centaurus A from an ATCA survey in the L2-0.7mm range. The most prominent lines are the C2H(C-4) line followed by the CO in the transition (1,1) and (2,2) which are used to trace the temperature of the gas.
NGC 1097: First spectral scan toward type-1 low-luminosity AGN

- New detections: H$^{13}$CN(1-0), C$_2$H(1-0), HNCO, CS(2-1), HC$_3$N(11-10)
- Possibly?: SiO (blended with H$^{13}$CO$^+$(1-0))
- Upper limit?: SO
Multi-molecular view of NGC 1097

Starburst ring is detected in HCN, HCO+, C2H, CS, and partly in HNCO
Comparison of 3mm line survey data in starburst galaxies ⇒ striking HCN enhancement w. r. t. CS !?
Serendipity – bright HC$_3$N in Mrk231 core

• Source size fit suggest upper limit of 300 pc –
  – Inner part of starburst disk?
  – Or in the shielded dusty gas near the AGN?

Need high resolution observations to pinpoint

• For T>300 K HC$_3$N abundances may become very high: 10$^{-6}$ in the dusty midplane gas near an AGN (Harada et al 2012)

• Signature of the final stage of the obscured, X-ray absorbed (Page et al. 2004) accretion phase of the QSO?

It puts the luminous HC$_3$N emission in some LIRGs and ULIRGs in a new light – is this a signature of a buried AGN (Aalto et al 2007, Lindberg et al 2011)?
Mrk231- high velocity molecular gas in the QSO outflow

ULIRG (log(LIR) = 12.37). Nearby infrared QSO + starburst with extreme SFR ≈ 200 M⊙ yr⁻¹

Wide, kpc-scale, high-velocity (≈ 1000 kms⁻¹) outflow seen in neutral gas (Rupke and Veilleux 2011). Line wings in CO 1-0 are v≈ 750 kms⁻¹

Molecular mass loss rate is 700 M⊙ yr⁻¹

Feruglio 2010
First detection of HCN, HCO$^+$, HNC 1-0 in an AGN wind dense (n>10$^5$ cm$^{-3}$) gas

IRAM Plateau de Bure – (Aalto et al 2012)

Outflow also detected in OH and H$_2$O absorption by Herschel (Fischer et al 2010, Gonzalez-Alfonso 2010)
Why would HCN be luminous in the outflow?

1. Dense clumps in the outflow? ”Raisin roll” scenario.
2. Mid-IR pumping of HCN?
3. Extreme HCN abundances?

Multi-wavelength information and modelling necessary to separate options.
High HCN abundances are expected in warm regions, in particular in AGNs (Harada et al 2010) and in shocks (Tafalla et al 2010).

Speculation: Will AGN driven outflows have elevated HCN emission? - and can that be an additional method of identifying the driving source?
Conclusions

• Molecular diagnostics offer a unique glimpse into the properties of AGN and starburst nuclei.
• Bulk temperatures and densities often high: T = 50-100 K, >100 K in inner 100 pc, n=10^3-10^5 cm^{-3} – but molecular diffuse medium surround dense clumps (”raisin roll”)
• Vibrational lines (HCN, HC_3N, HNC) trace optically thick dust cores of T_B(IR)=200-500 K. Can help find buried AGNs?
• New masers detected: HNC
• Chemistry will become powerful diagnostic tool with ALMA:
  – HCN/HCO^+, HNC, H_2O, H_3O^+ (hydronium), HC_3N, C_2H, CH_3OH, H_2CO, isotopic variants etc
  – Can help date evolutionary state of starburst – distinguish between different types of starbursts.
  – Still looking for unambiguous tracer of AGN chemistry – H_3O^+ promising candidate.