Cold gas in the nuclear region (~500 pc) of M31 -- CO and [CII] mapping of selected regions

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Background

• Supermassive black hole (SMBH) and host galaxy coevolution: how does a SMBH influence the nuclear region? Physical properties of the interstellar medium (ISM).
• Why M31? Distance: 780 kpc, i.e. 1” ≈ 4 pc: M31 is the nearest large spiral galaxy that can see the nuclear region from outside in detail.
• M31: similar to the Milky Way (MW), but has a much larger bulge and less obvious spiral arms, with most Star formation occurring in a 10 kpc ring. Good comparison to the MW.
Nuclear region of M31

- A 1 kpc filament across the nucleus: nuclear spiral: how does it form? Interaction with other galaxy (e.g. M32, Block+ 2006) or bar resonance (Lewis+ 2015)?
- SMBH mass: $\sim 10^8 M_\odot$; luminosity: $\sim 10^{-10} L_{\text{Edd}}$: little AGN activity
- Lack of recent SF and massive stars (Li+ 2009, Dong+ 2015)
- M31: the closest low-ionization nuclear emission line region (LINER): ionization mechanism?

**Key to these questions: multiphase ISM!**
Previous surveys show limited neutral gas detections in the circumnuclear region of M31. (e.g. Braun 2009, Nieten 2006)

In comparison, the Milky Way has a central molecular zone (CMZ) that is rich in gas.
1. Molecular gas in the nucleus

- Deep CO(3-2) observations with 15 m JCMT/HARP raster mode (25 hrs):
- First CO(3-2) survey covering central ~3’ radius

Color map: dust mass surface density. White contour: CO(3-2). Black contour: CO(1-0).

CO(3-2)/CO(2-1) ~ 0.8

CO(3-2)/CO(1-0) ~ 0.9

- Other nearby galaxy: ~0.2 (Wilson+2012)
- Luminous infrared galaxy: ~0.5 (Leech+2010)
Molecular gas properties

- Large velocity gradient (LVG) assumption with RADEX code:
  - $\text{CO}(3-2)/\text{CO}(1-0)$ ($R_{31}$) $\sim$ 0.90: $T_k > 20$ K and $n(\text{H}_2) > 4 \times 10^3$ cm$^{-3}$;
  - $\text{CO}(3-2)/\text{CO}(2-1)$ ($R_{32}$) $\sim$ 0.8: $T_k > 30$ K and $n(\text{H}_2) > 2 \times 10^3$ cm$^{-3}$.

HST extinction map (A547M, Dong+ 2016):
- $A < 1$ -> low column density.
- Rotation pattern, nuclear disk -> low density: $n(\text{H}_2) \sim 10^3 – 10^4$ cm$^{-3}$.

- Molecular gas mass: $3.7 \times 10^5 M_\odot$, compared to $\sim 10^7 M_\odot$ in Milky Way CMZ.
- H$\text{}_2$/dust ratio: $\sim 30$ in the central region: higher metallicity (Draine+ 2014)
2. HARP and SCUBA-2 High-Resolution Terahertz Andromeda Galaxy Survey (HASHTAG)

- JCMT large program: first ground-based submillimeter continuum survey of the Andromeda. (273.6 hr)
- SCUBA-2: 450 μm (25 pc) and 850 μm (50 pc) very cold dust survey for entire M31.

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HARP CO observations

• **HARP CO(3-2) observations**: Eleven 2’ x 2’ jiggle fields, one 4’ x 4’ raster field (55.3 hours in total). Mean rms: 0.013 K $T_A^*$

1. Five regions covered by Herschel and optical IFU spectroscopy
2. Two regions where it has been suggested to have a component of very cold gas
3. Four in the area observed by PHAT, CARMA and the IRAM CO(1-0)/CO(2-1)

• For now: focusing on the CO(3-2)/CO(1-0) ratio.
CO(3–2) in the disk

Black: CO(1–0), red: CO(3–2)

Credit: Matt Smith

Findclump to label clumps in 3D

Color map: dust, black contour: CO(3–2), white contour: CO(1–0)
**CO(3-2)/CO(1-0) ratio ($R_{31}$)**

- Nuclear region: $\sim 0.8$
- Mean ratio of the 10 kpc ring: 0.27
- Mean ratio of the inner disk: 0.14

- M31 Nucleus: $\sim 0.8$, Disk: $\sim 0.23$.
- Galactic center: $\sim 0.7$, Galactic disk: $\sim 0.4$ (Oka et al., 2012)

- LVG model: The lowest value 0.14 only requiring a kinetic temperature $> 5$ K.

- Dust temperature – $R_{31}$:
  
  Spearman’s rank correlation coefficient $\rho$: 0.55, p-value: < 0.001

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Draine et al. 2014
3. FIR lines in the circumnuclear region of M31

- Herschel PACS observation of [CII] 158 µm, [OI] 63 µm and [OIII] 88 µm, covering a 2’ x 2’ region in the center (‘Nucleus’).
- O++: ionized gas; C+: exists in ionized, atomic, molecular gas; O: neutral gas -> physics in photodissociation region (PDR)
- Five 3’ x 3’ fields on the disk, from Kapala et al. (2015), mainly [CII]. (‘a-e’
Morphology and kinematics

- [CII], [OI] consistent with CO and dust emission
- [OIII] consistent with Hα emission
- [OI] has double components: from two different arms
PDR modeling

- Photo Dissociation Region Toolbox (PDRT; Pound & Wolfire 2008; Kaufman et al. 2006): 2D slab PDR illuminated by FUV from one side.
- \([\text{OI}] / [\text{CII}], \([\text{OI}]+[\text{CII}]\)/FIR, \([\text{CII}]/\text{CO}(1-0)\) ratios as diagnostics to constrain gas density \(n\) (cm\(^{-3}\)) and incident FUV intensity \(G_0\) (1.6 \times 10^{-3} \text{ erg cm}^{-2} \text{s}^{-1})

Uncorrected
- \([\text{CII}]\) from ionized gas (Lapham et al. 2017)
- Illuminated from both sides: FIR/2

Corrected:
- 53\% \([\text{CII}]\) from ionized gas

Best-fit:
- \(n: 10^3\)
- \(G_0: 3.16 \times 10^2\)

Milky Way:
- \(n: 10^{3.5-4}\)
- \(G_0: 1-30\)
  (Pineda et al. 2013)
Take home messages

- $R_{31}$ ratio is higher in the central region (0.8) than in the disk (0.14), and rise again in the 10 kpc ring (0.27).

- From PDR modeling, we can derive gas density $n \sim 10^3$ cm$^{-3}$ and FUV intensity $G_0 \sim 3.16 \times 10^2$ (in units of $1.6 \times 10^{-3}$ erg cm$^{-2}$ s$^{-1}$).

Cold gas in the circumnuclear region is little but hot, and suffered from a high radiation field!
Follow-up programs

Follow-up IRAM 30m CO(1-0) and JCMT CO(3-2) mapping of the nuclear region:

- Help reveal the origin of the nuclear spiral.
- Complementary of HASHTAG CO observations.

Left: dust surface density map (Groves 2012). Right: H$\alpha$ map. Dashed ellipse marks the nuclear ring.