Herschel PACS Spectroscopic Diagnostics of Local ULIRGs

Conditions and Kinematics in Mrk 231

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with SHINING team

(see also our A&A 2010 Special Issue paper)

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Why study local ULIRGs?

- In the local Universe, ULIRGs signal the merging and morphological transformation of gas rich galaxies: what are their evolutionary precursors, products and how do they reach them?
- They're a major contributor to the IR background.
- ULIRGs: often the first galaxies we'll learn about at high z.
- In what ways and which high-z ULIRGs are like local ones?
- Unique ISM: warm, high far-infrared radiation density, molecular and possibly opaque, so our task is not easy, but we have a great observatory to help us out!

SHINING ULIRG Observations

- About 80 hrs is devoted to PACS spectroscopy of ULIRGs
- Full PACS highly sampled scan of Arp 220
- Range scans ≥ (±1000 km s^{-1}) of all RGBS galaxies with
- $L \geq 10^{12} L_{\odot}$ plus NGC 6240 and UGC 5101 (23 galaxies):
  - Fine-structure lines tracing atomic and ionized gas, [CII]158, [OI]145,63, [NII]122, [OIII]88, [NIII]57
  - ^{16}OH 119, 79 μm, ^{18}OH 120 μm, lines
  - H_2O 78.7 μm, 121.7 (HF 2-1) lines
  - CO (20-19)

Mrk 231, a type I LoBAL ULIRG

- Most luminous of the local ULIRGs in the RBGS, $L_{IR} = 3.2 \times 10^{12} L_{\odot}$ for adopted distance, 172 Mpc (z=0.04217)
- Central quasar is covered by a semi-transparent dusty shroud producing about 3.1 magnitudes of extinction at 4400 Å (Reynolds et al. 2009)
- Low ionization broad absorption is observed, eg. in Na I D, at both high velocities (up to ~ 8000 km/s) and lower velocities (up to ~ 2000 km/s)
- Mid-IR/Spitzer: Veilleux et al. (2009) the AGN contribution to L_{bol} is ~ 70% by most of 6 estimation techniques (vs 35 – 40% for all ULIRGs)
- Contribution of an advanced 120 – 250 Myr nuclear starburst is ~ 25 – 40% (near-IR, Davies et al. 2007)
- Dominated by molecular absorption in the far-IR (Gonzalez-Alfonso et al 2008)
- Nuclear rotating, nearly face-on molecular disk (Downes & Solomon 1998)

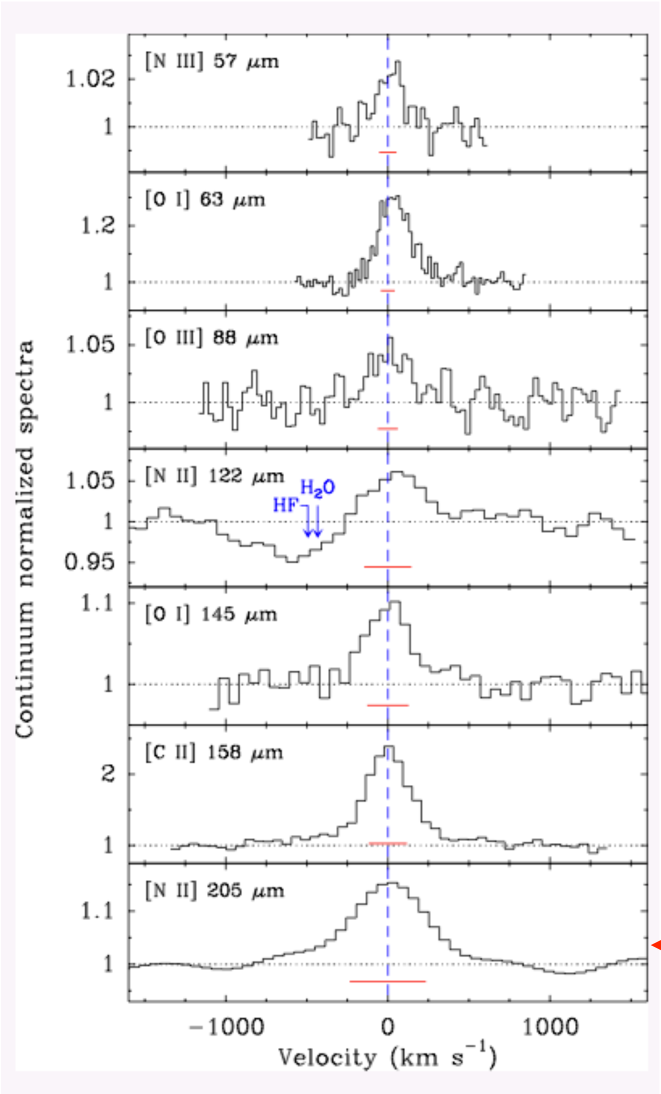
Fine Structure Lines & Kinematics

All searched for fine-structure lines were detected in a ULIRG for the first time! They are faint!

Inferred FWHMs are in the range 180 - 290 km/s, Δv_{avg} = 235 km/s

This early in the mission the best calibration is on the continuum of Mrk 231 itself, ≥ 25%

Blue wing (out to -1000 km/s) is evident in [CII], [NII], and possibly the HF/H2O line



Fine-structure FWHMs similar to those of CO(1-0) and stellar disk 170 & 270 km/s

The blue wings have similar velocities as “low” velocity, kpc scale outflow components (v> -2100 km/s, Veilleux et al. 2005)

[N II] 205 µm
HerCULES SPIRE FTS
(HerCULES KP)
van der Werf et al. 2010

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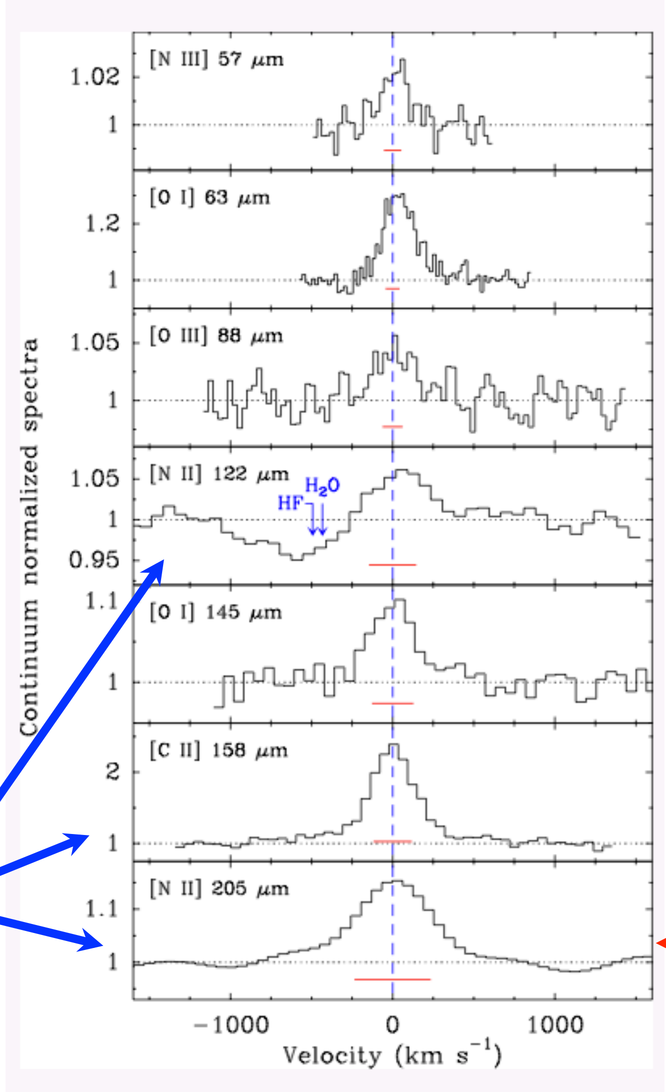

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Fine-structure line deficit trends

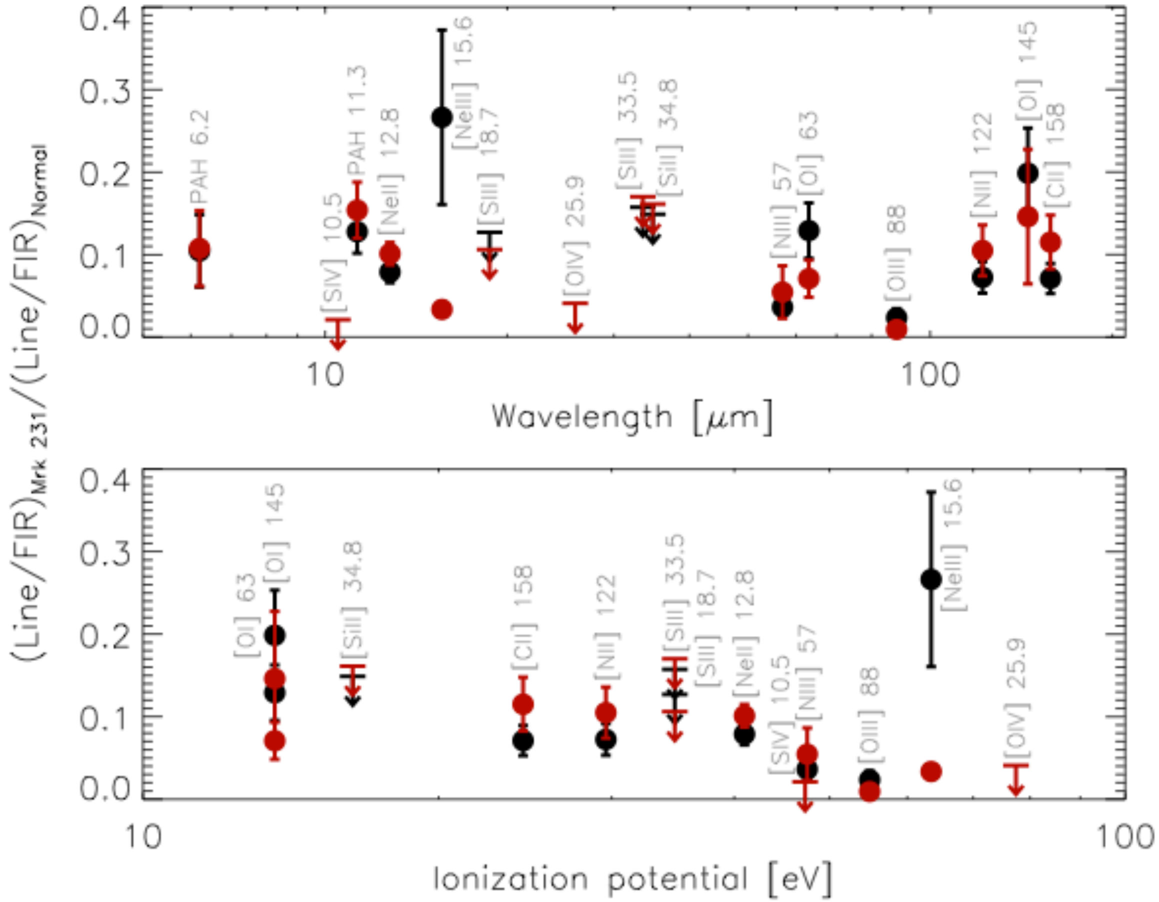
No obvious trend in the deficit with transition λ (or n_{crit}) compared with AGN & SB

Deficit is more severe for higher ionization potential compared with AGN & SB, but for SB, [NeIII] is strong

- ● Starburst sample
- ● AGN sample

*Comparison samples
Graciá-Carpio et al., in prep.
Poster session 1

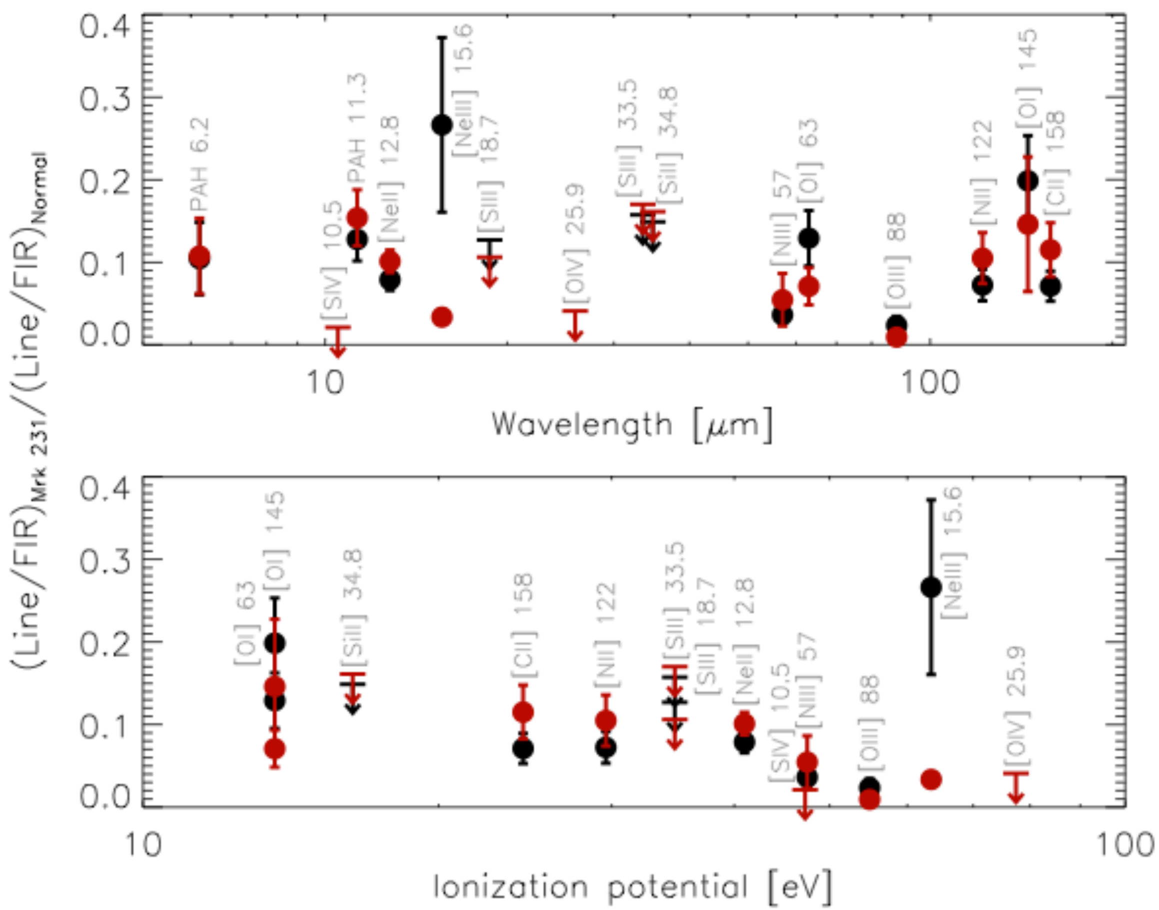
(Spitzer lines from Armus et al 2007)



Fine-structure line deficit trends

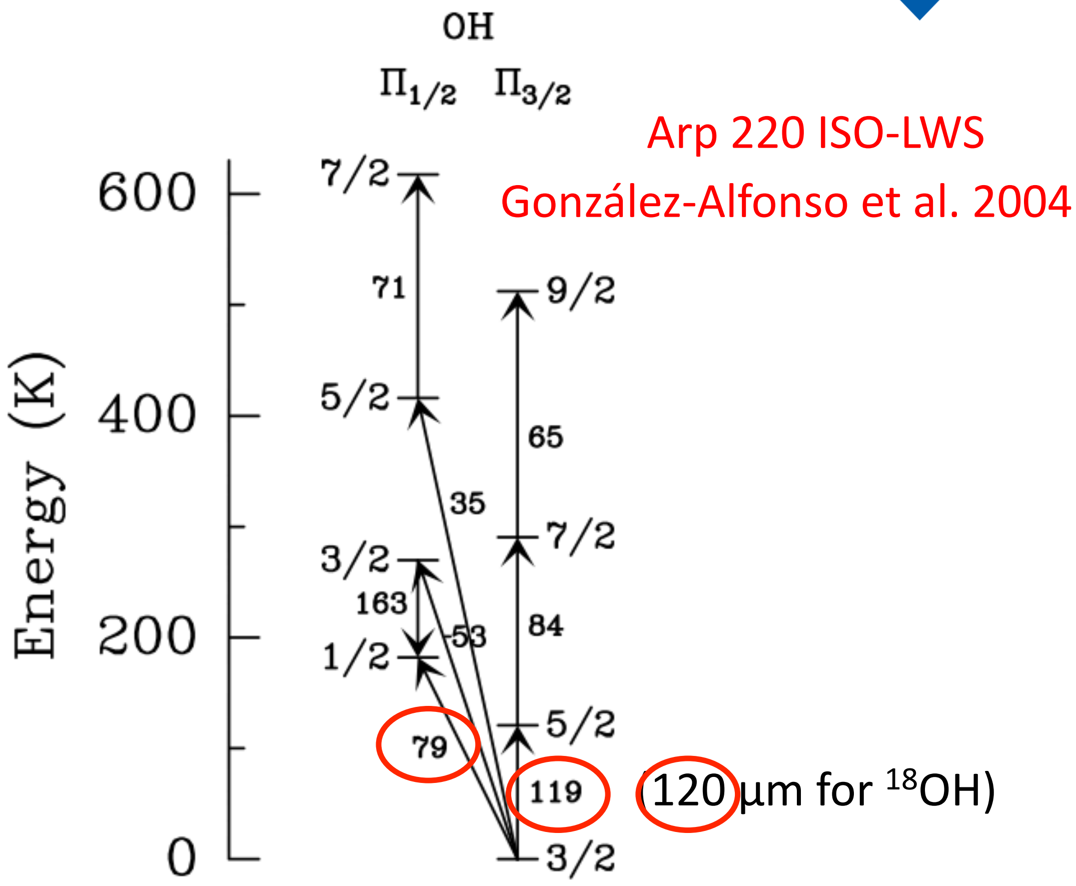
(Spitzer lines from Armus et al 2007)

If the deficits are caused by dust obscuration, it appears to be caused by extremely opaque clumps, all or nothing, with higher covering for species with higher ionization potentials



Observed OH, ^{18}OH transitions

In addition to the fine-structure lines, we observed the strong OH 119, 79 µm & the ^{18}OH 120 µm doublets in Mrk 231



A massive molecular outflow

Spectacular P-Cygni profiles in both OH, and the ^{18}OH ground-state doublets with broad blue-shifted absorption as far out as -1400 km/s for OH 119 µm

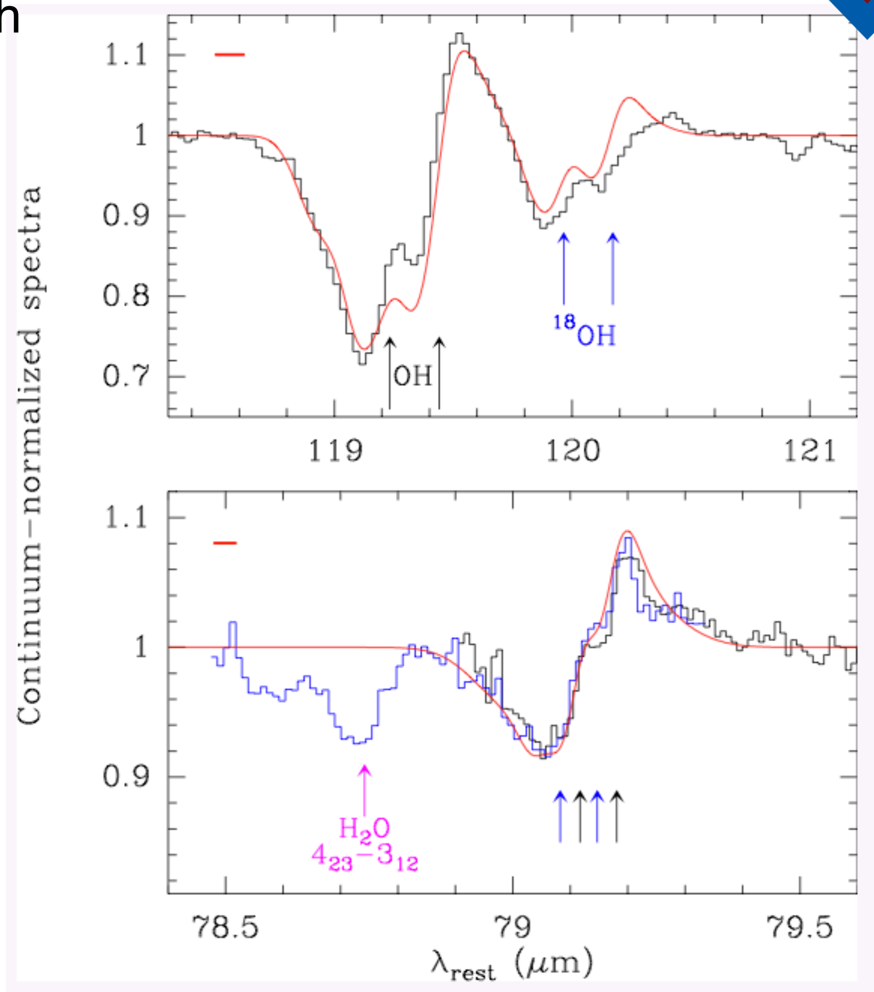
Blue-shifted wings suggest that [CII], [NII], & excited H_2O/HF also participates in the outflow

Based on model fits to continuum and line pumping (Gonzalez-Alfonso 2010), outflow lower limits:

Mechanical energy ≥ 10^{56} ergs,

Mechanical luminosity ≥ 1% of L_{TIR},

Mass ≥ 7×10^{7} $M_\odot$



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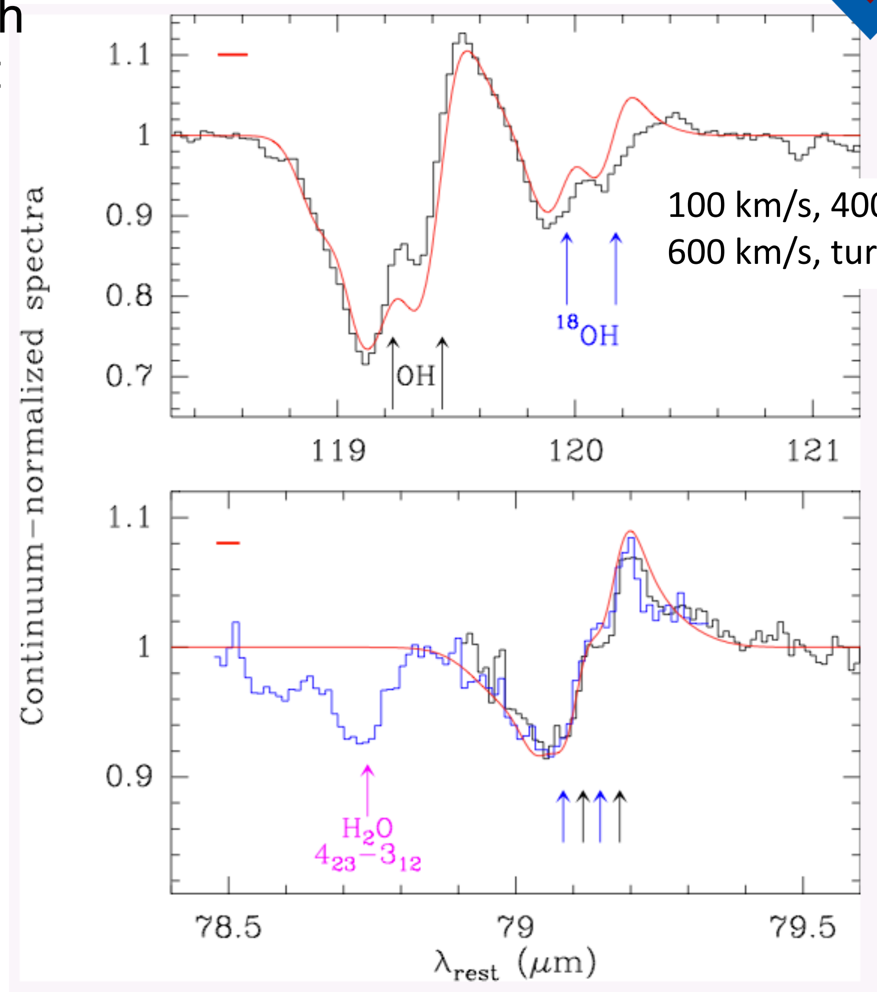
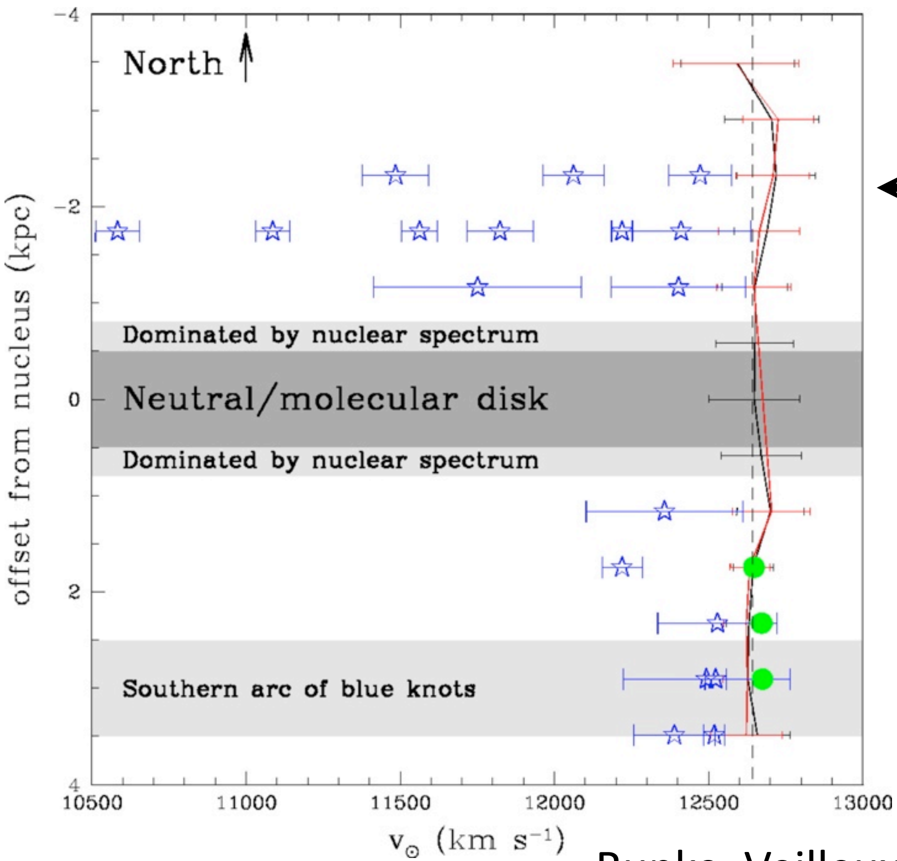


100 km/s, 400 km/s, 600 km/s, turb=300 km/s

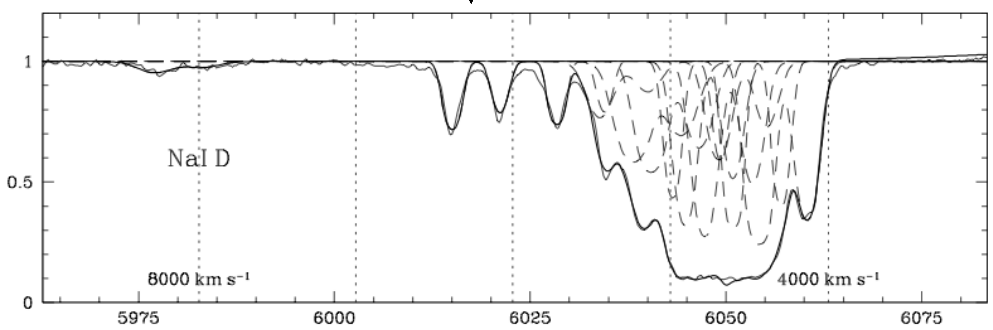
Comparison to Na I D doublet

Molecular Outflow traced by OH



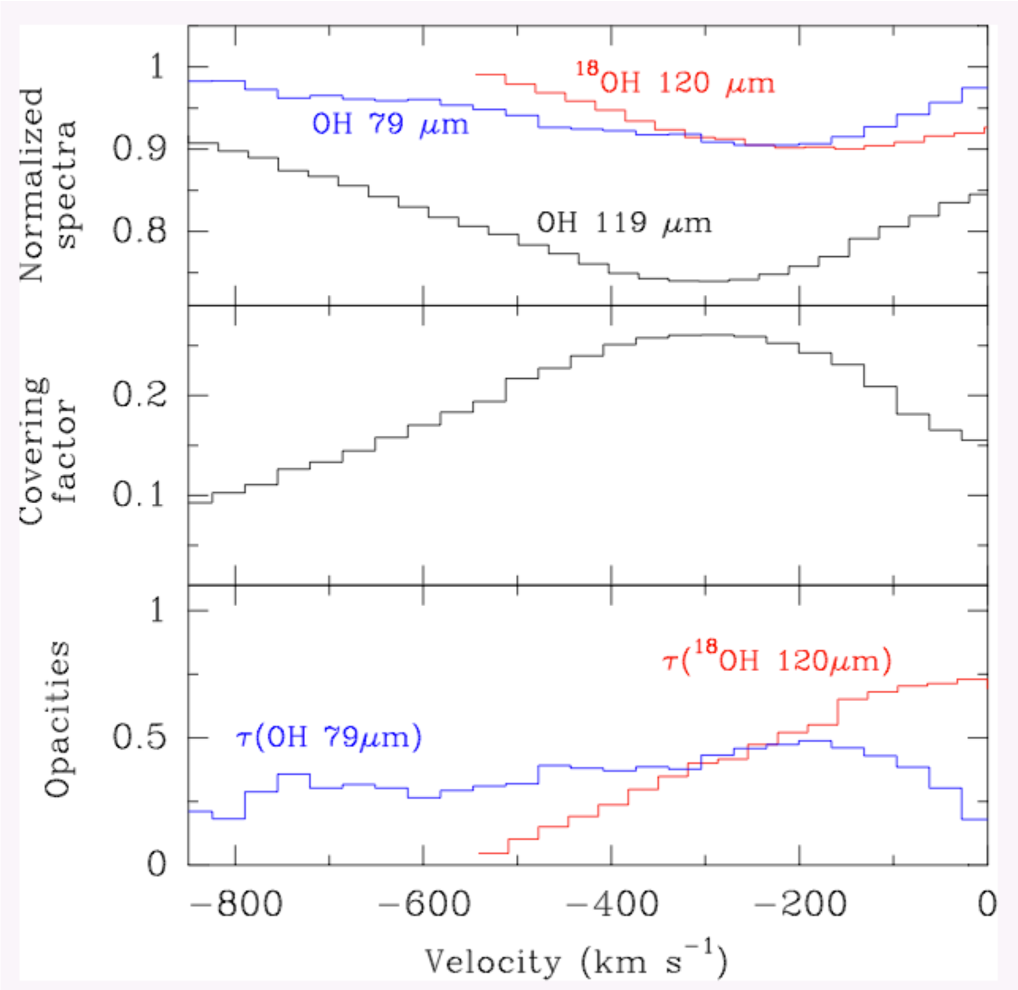
Blue shifted velocity range suggests kpc scale, similar to Na I D optical outflow velocities

Not the nuclear -8000 – -4000 km/s, (whose velocities were not observed)



Rupke, Veilleux & Sanders 2002, 2005

High $^{18}O/^{16}O$ abundance



^{18}OH 120 µm absorption is deeper than OH 79 µm at low negative velocities (top)

We use the covering factor measured from 119 µm (middle); not too sensitive to this

At these velocities, it appears that:

$\tau(^{18}OH\ 120) \geq 40\ \tau\ (OH\ 79)$ (bottom)

$N(^{18}OH)/N(OH) > 40$

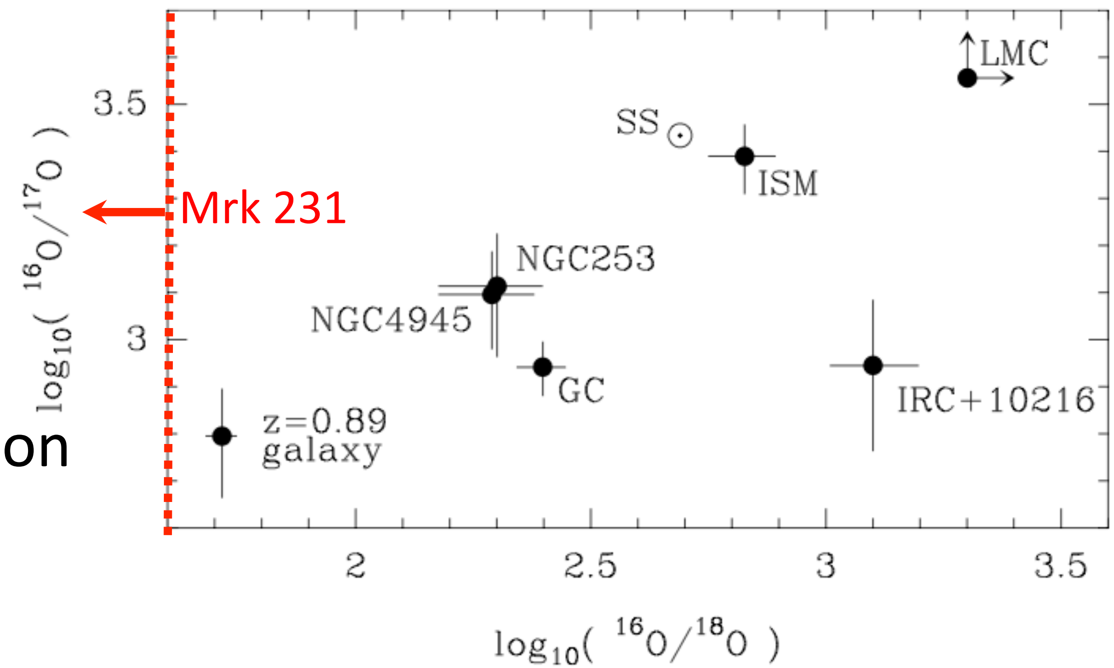
Need observations of high OH levels

Extreme $^{18}O/^{16}O$?

If our analysis is correct (need higher $OH/^{18}OH$ line profiles, to confirm it), Mrk 231 may be even more extreme than a z=0.89 along the line of sight to a quasar in $^{18}OH/^{16}OH$.

For Mrk 231 it is not possible to constrain the $^{16}OH/^{17}OH$ but this should be possible for lower velocity outflows where there is better separation of the ^{16}OH and ^{18}OH lines

Muller, S. et al. 2006



If true, this suggests stellar processing by an advanced starburst with a top heavy IMF

Summary

- The IR fine-structure lines Mrk 231 are faint compared with both star-bursts and AGN, by ~ 1-2 orders of magnitude
- No correlation of line deficits with λ, weak correlation with n_c, but strong inverse correlation with ionization potential (IP) compared with AGN, and compared with starbursts up to the NeIII 15 μm line at IP ~ 60 eV. This may be an effect of higher covering factors for higher IP, possibly from a clumpy medium
- The OH lines show P-Cygni profiles indicating a kpc scale massive molecular outflow. Some H_2O, [CII], [NII], & HF appears to participate in the outflow
- $^{18}O/^{16}O$ appears very high compared with other galaxies, suggesting strong stellar processing by a top-heavy IMF, but this needs follow-up with higher excitation OH lines