AGN Jets and Winds: Shocking the ISM

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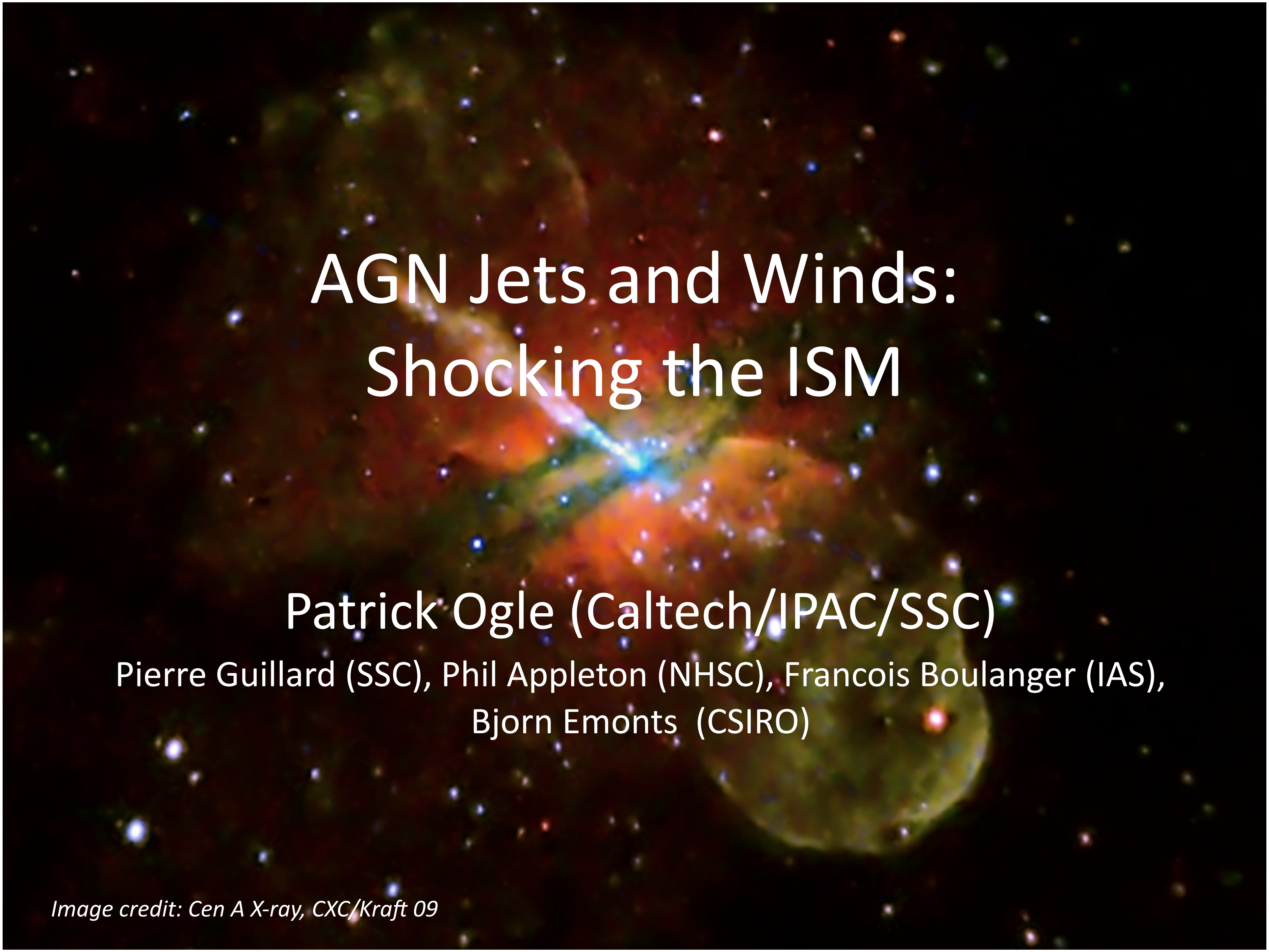
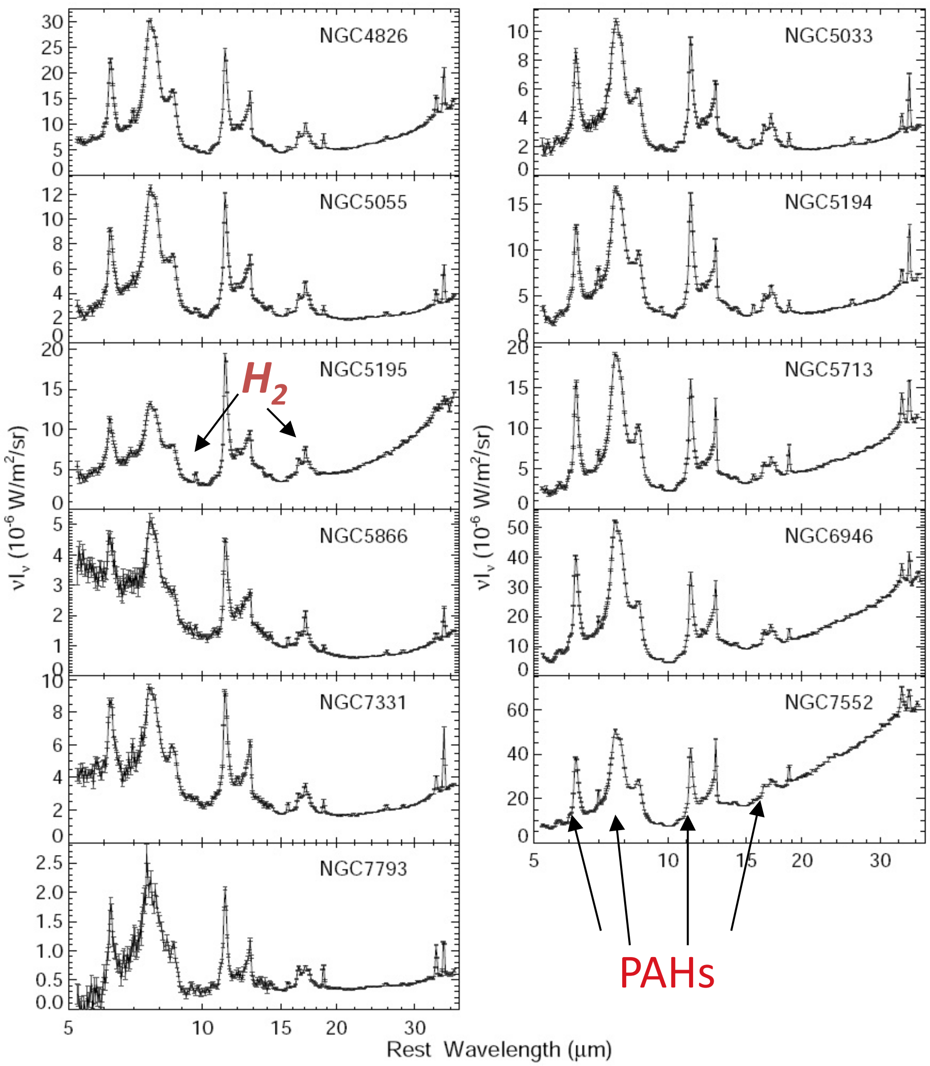


Image credit: Cen A X-ray, CXC/Kraft 09

Normal Star-Forming Galaxies



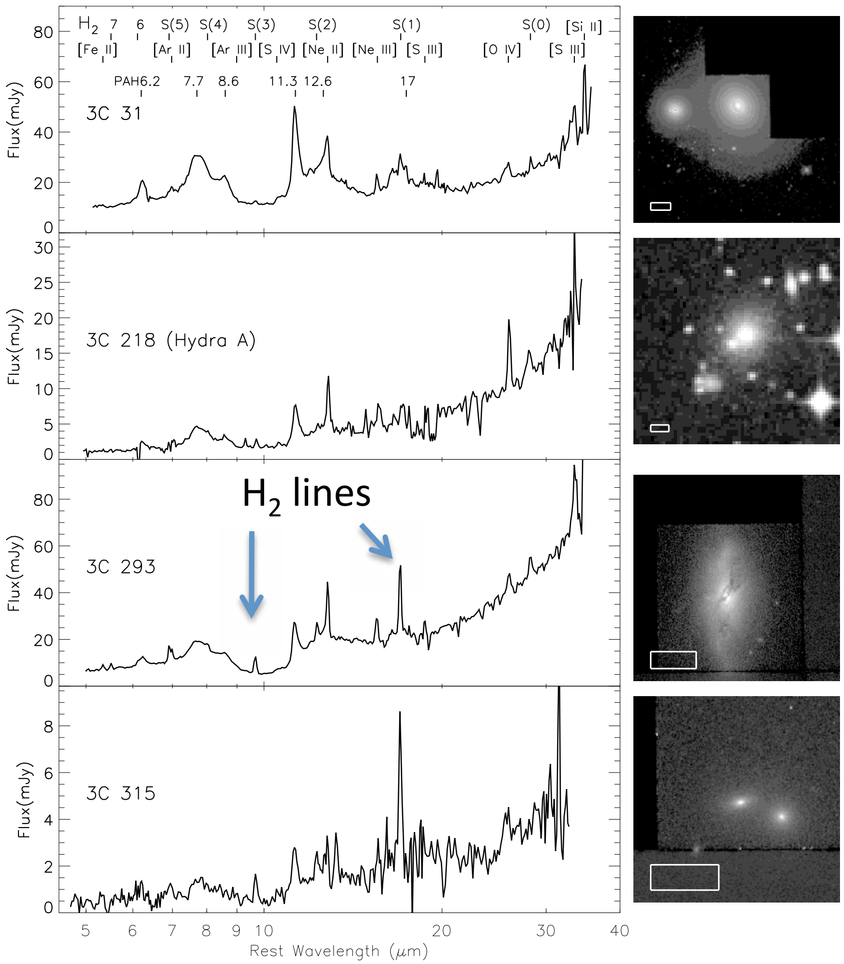
Spitzer SINGS survey (Smith 07)

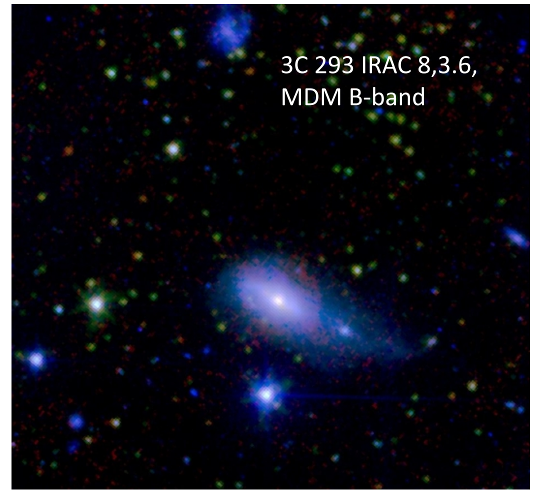
•Polycyclic Aromatic Hydrocarbon (**PAH**) dust is excited by UV photons.

• The 7.7 μm feature is useful for estimating star formation rate.

•H_2 emission is weak.

Radio Galaxies with H_2 Emission





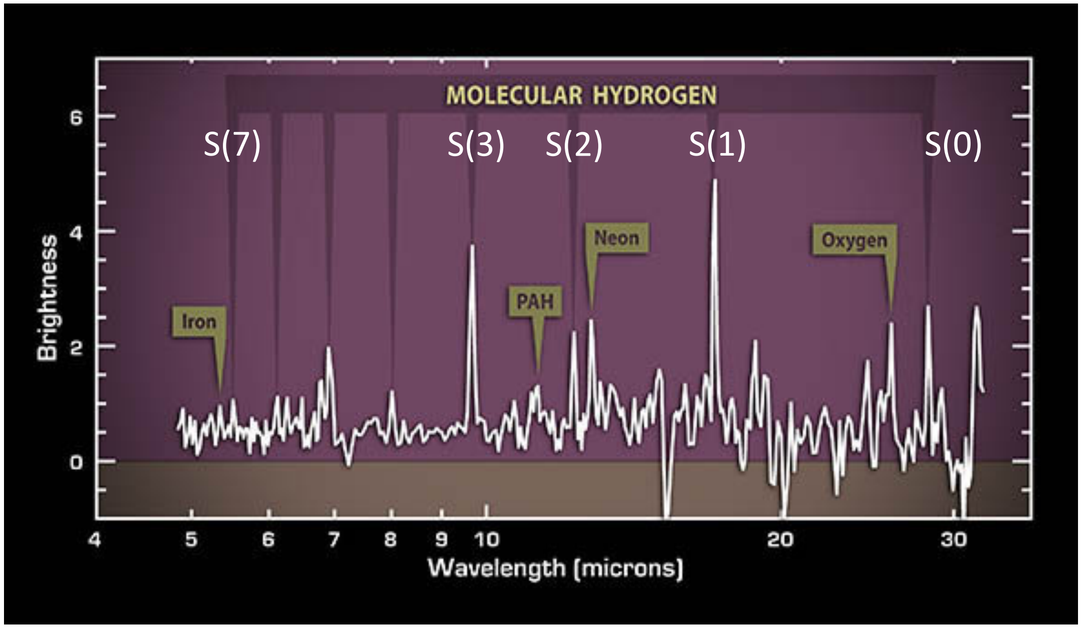
Spitzer IRS radio galaxy survey:
30% of 3C radio galaxies at z<0.2 have strong $\mathbf{H_2}$:

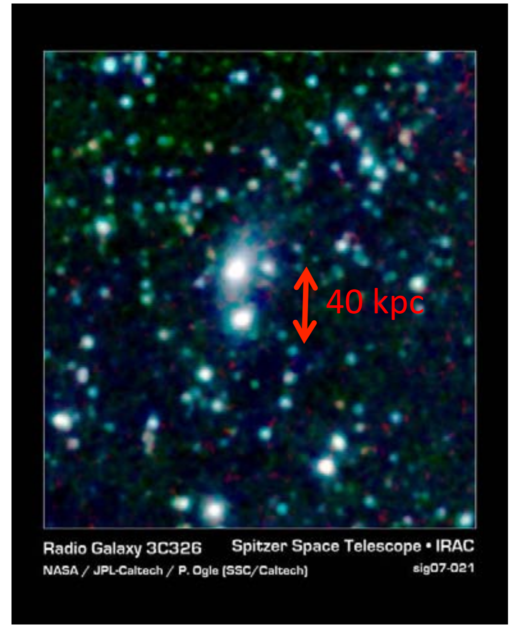
$M(H_2, T>100\ K)=10^7\text{-}10^{10}\ M_\odot$

Environment:
-Nearly all have interacting companions.
-One third live in cool-core clusters.

3C Radio Galaxies (Ogle 10, 07)

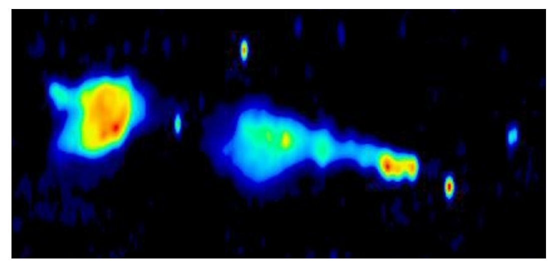
Radio Galaxy 3C 326 (z=0.089)





Spitzer IRS rotational $\mathbf{H_2}$ lines (Ogle 07):

- -L($\mathbf{H_2}$)=9×10^{41} erg/s
- -L($\mathbf{H_2}$)/L_{IR}~0.1
- -M(warm $\mathbf{H_2}$)=2×10^{9} $M_\odot$
- -M(cold $\mathbf{H_2}$) =2×10^{9} $M_\odot$ (CO, Nesvadba 10)
- -SFR<0.2 $M_\odot$ yr^{-1}



1.9 Mpc radio lobes (Leahy).

Other H_2 Emission Galaxies

A variety of galaxy types show strong H2 emission:

-NGC 6240 LIRG; ULIRGs (Joseph 84, Lutz 03, Higdon 06)

-Cool core cluster galaxies
(Donahue 00, Egami 06, Johnstone 07, de Messières 10)

-AGNs (Rigopoulou 02, Roussel 07); QSOs (Schweitzer 06, Veilleux 09)

-Stephan's Quintet intergalactic shock (Appleton 06, Cluver 10)

-Radio galaxies (Ogle 07,10; Willett 10, Guillard 11)

-Dusty ellipticals (Kaneda 08)

-Stripped cluster galaxies (Sivanandam 10)

In all of these galaxies, something is disturbing and heating the molecular gas…

What Powers H_2 Emission in Radio Galaxies?

Radio Jet Feedback ---jet kinetic power (~10^{44} erg s^{-1})

Jet K.E. dissipation (~10^{42} erg s^{-1}) in multiphase ISM

a) Hot (10^7 - 10^9K) cocoon of shocked gas

b) Shocked molecular and atomic clouds

c) Ionized and neutral gas outflows

d) Cosmic ray heating (Ferland 08)

Galaxy Mergers and Cooling Flows provide the gas

a) Companions and interaction/mergers prevalent

b) One third reside in cool core clusters, the rest in groups/pairs

c) Must accrete ~0.1-10 $M_{\odot}$/yr onto 10^{11} $M_{\odot}$ host

AGN X-rays

-In most cases the AGN is not enough to power the H_2 (~10^{41} erg s^{-1}).

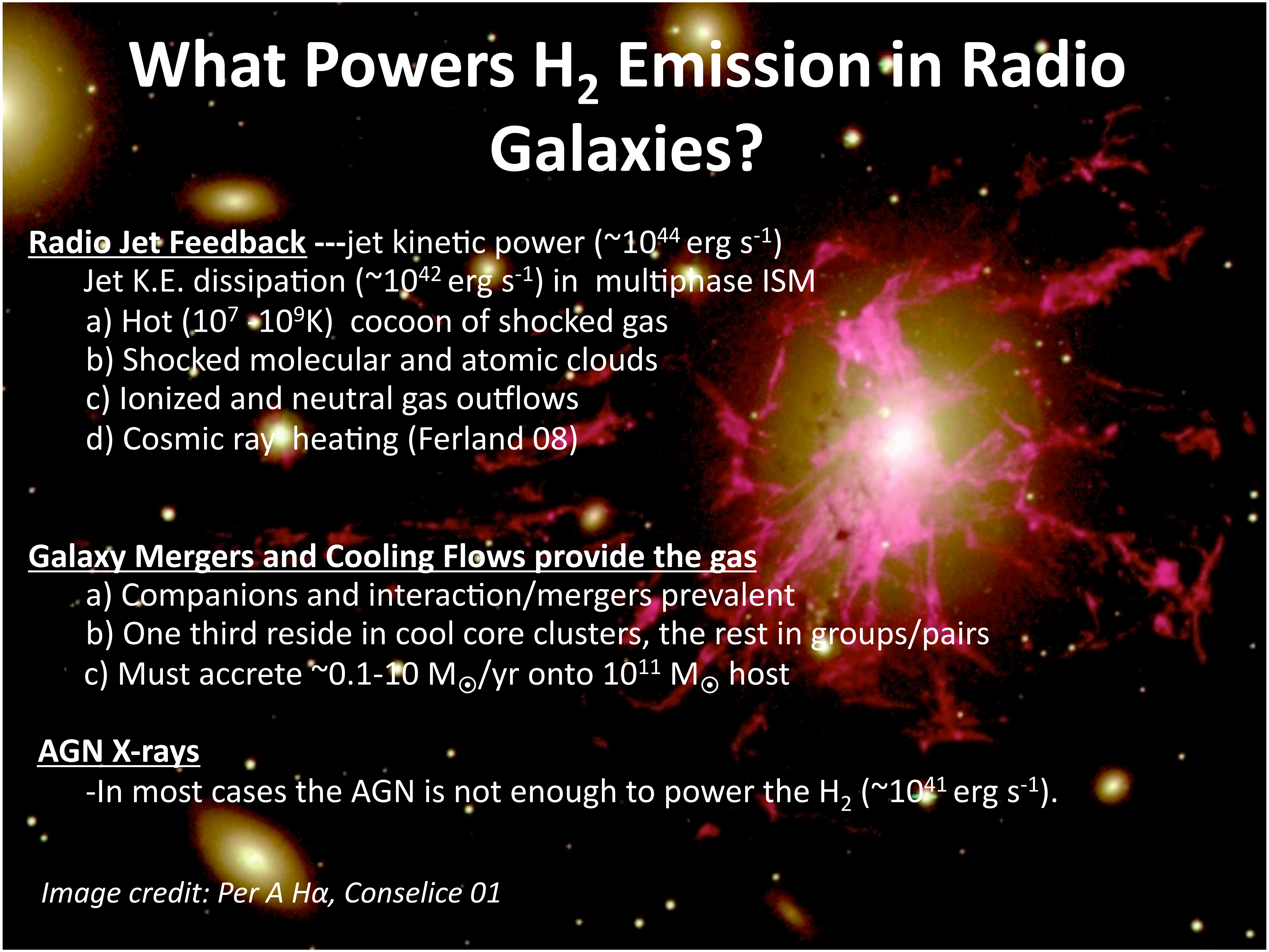
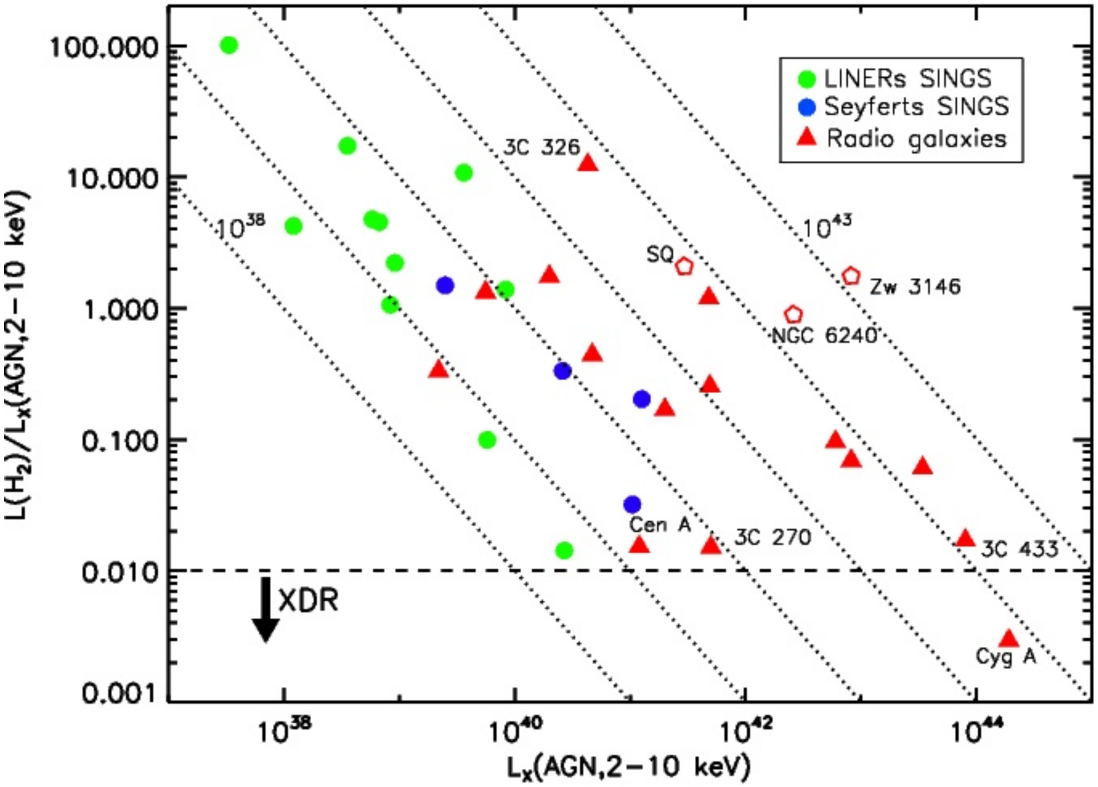


Image credit: Per A Hα, Conselice 01

Insufficient AGN X-ray Heating (XDR)

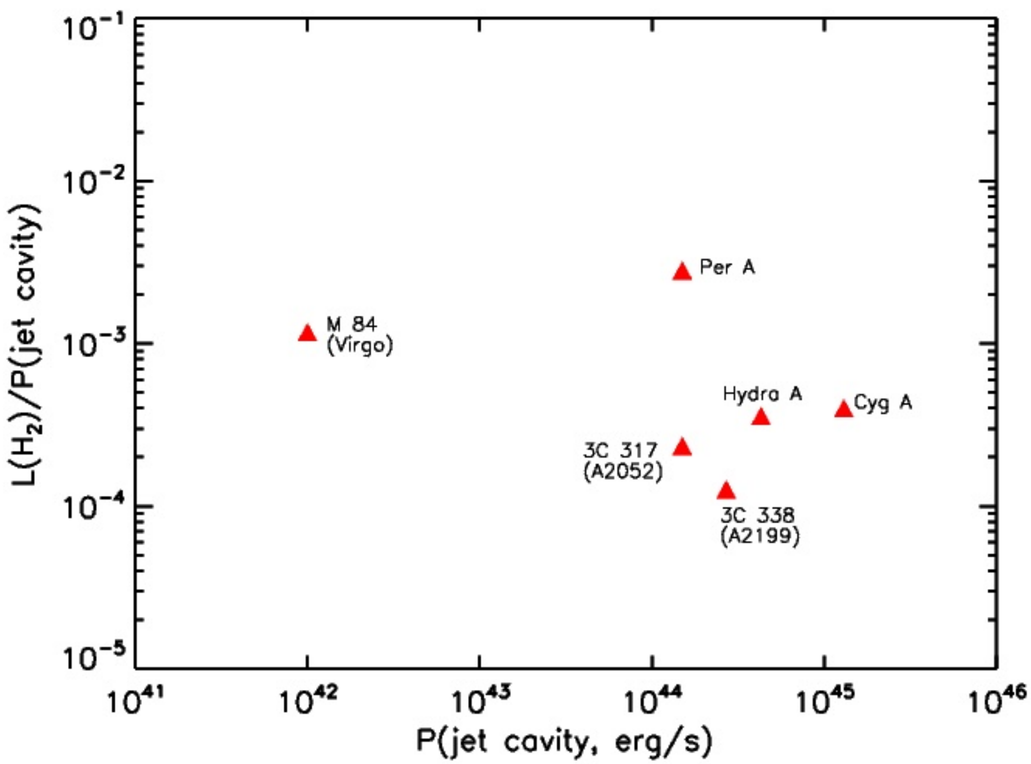


X-ray Power

•AGN X-rays observed with Chandra are too weak to power the H_2. (Ogle 10)

• XDR: $L(H_2\ S(0)\text{-}S(3))/L_X(2\text{-}10\ keV)<0.01$ (est. from Maloney 96)

Radio Jet Mechanical Heating



Radio Jet Cavity Power

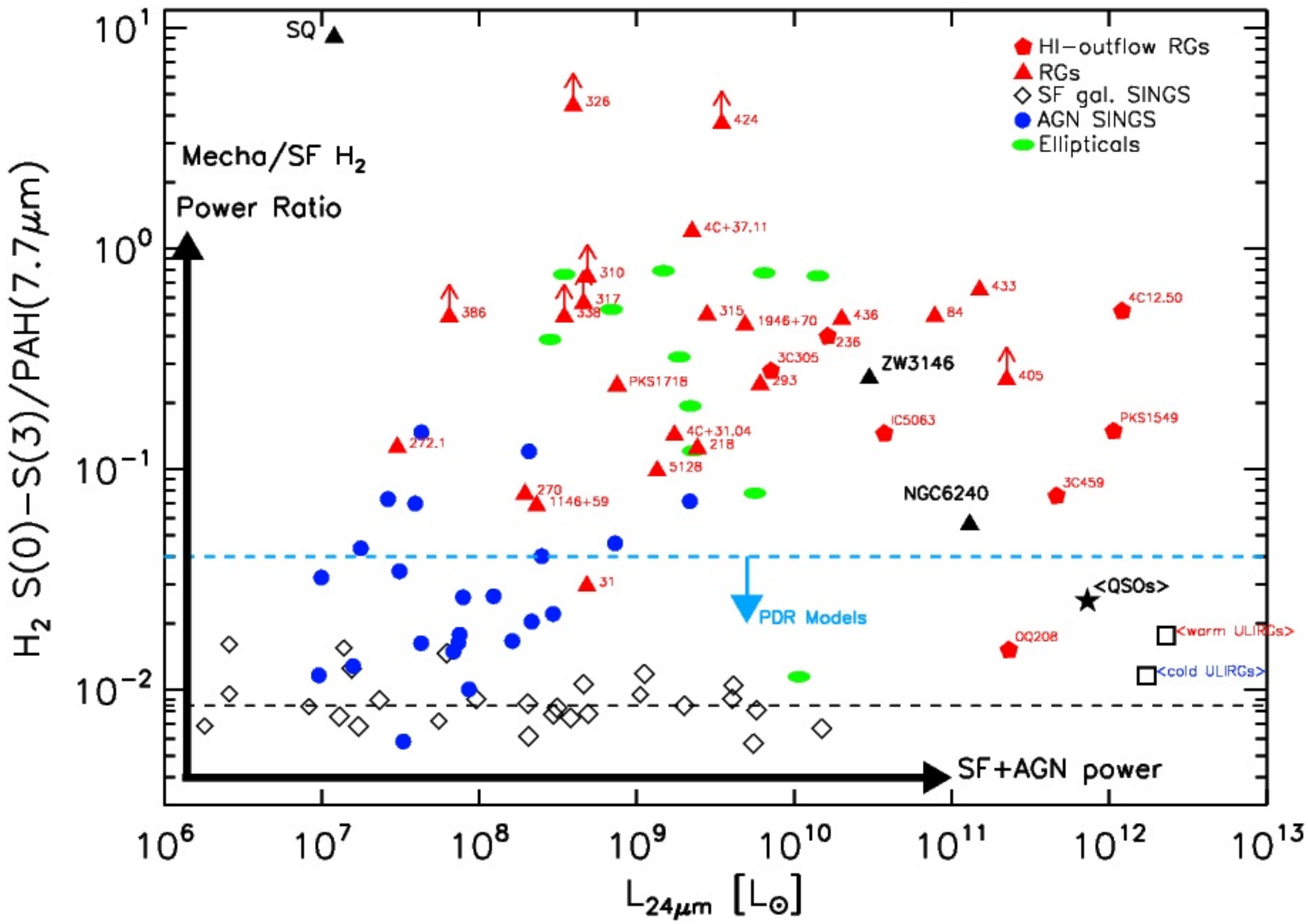
- Radio jet cavity powers measured for 6 H_2 luminous radio galaxies. (Rafferty 06; Bîrzan 04)

- P(jet cavity) = 4pV/t(bouyant)
  p,V, t estimated via ***Chandra.***

- L(**H_2**)/P(jet)=10^{-4} - 2×10^{-3}

- ***H_2 cooling time ~10^4 yr.***
  --Requires sustained heating by jet or kinetic/turbulent energy reservoir.

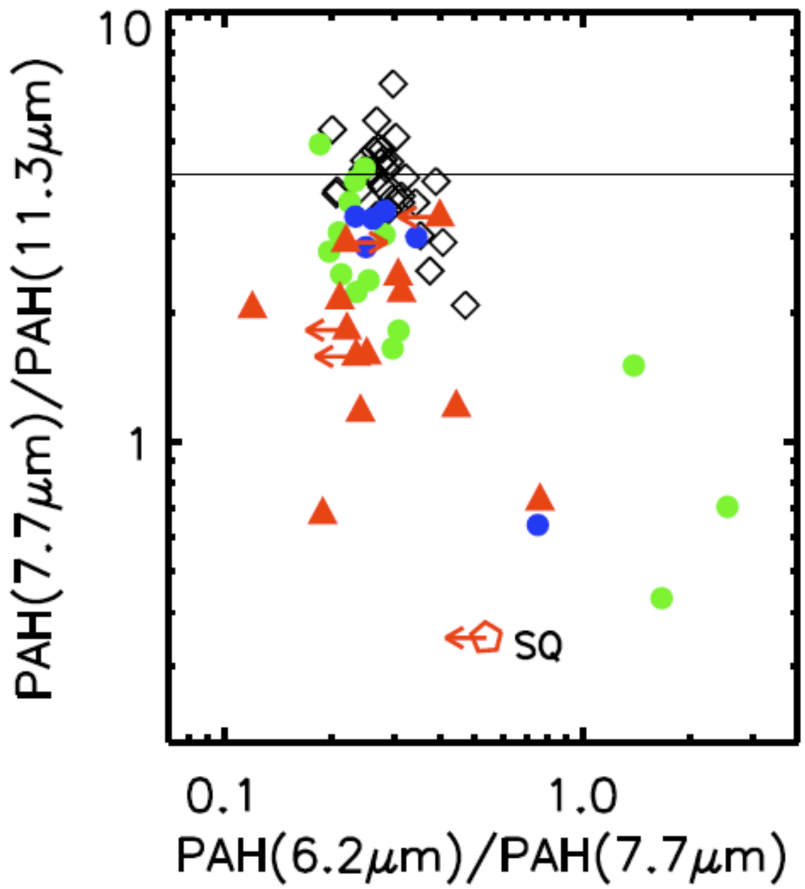
Shocks vs. PDRs



MOHEGs (Ogle 07, 10; Guillard 11) :
MOlecular **H**ydrogen **E**mission **G**alaxies
L(**H_2**)/L(7.7 μm **PAH**)>4×10^{-2}

Star forming galaxies (Roussel 07):
L(**H_2**)/L(7.7 μm **PAH**)~8×10^{-3}

Weak UV Field and PAHs in Radio Galaxies



•Radio galaxies (red triangles) have
-low PAH7.7/PAH11.3
-normal PAH 6.2/PAH7.7

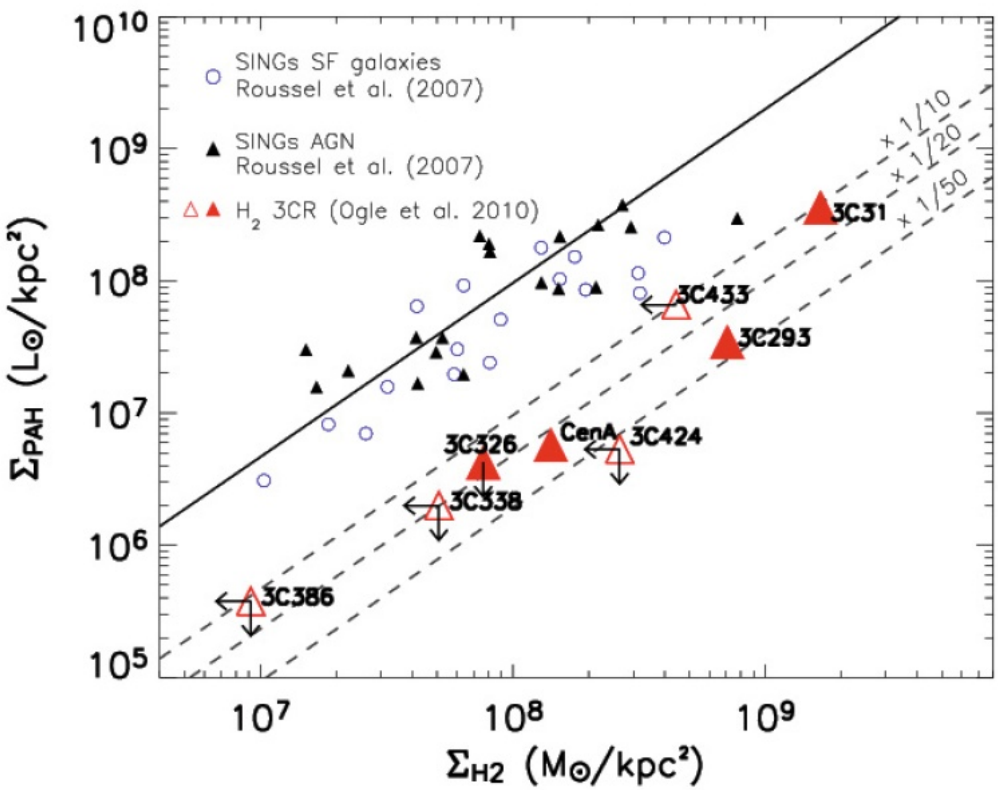
-compared to SINGS galaxies (diamonds) and AGNs (blue/green circles)

PAH ratios in RG with low SFRs are similar to the MW diffuse ISM…

…Large H_2/PAH attributed to weak UV field, NOT PAH destruction.

(Ogle 10)

Radio Jet Feedback on Star Formation



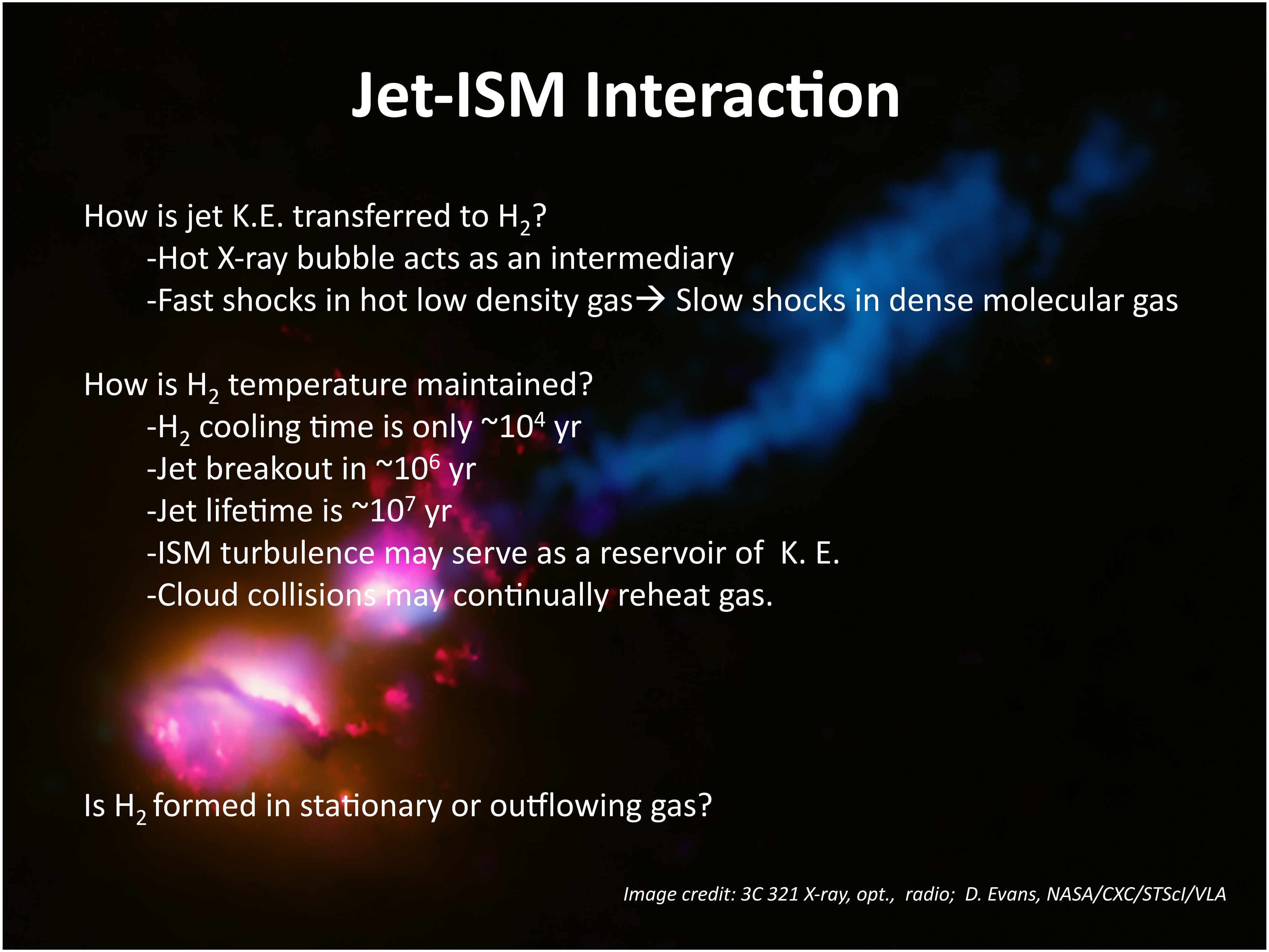
MIR Kennicut-Schmidt diagram: Nesvadba 10

- Specific star formation rates in radio MOHEGs are suppressed by a factor of 10-50 compared to SINGS SF galaxies. (Nesvadba 10)

- PAH emission used to estimate SFR in Spitzer IRS slit.

H_2 emission from Spitzer is supplemented by ground-based CO Observations to estimate Σ_{H2}

Jet-ISM Interaction



How is jet K.E. transferred to H_2?

-Hot X-ray bubble acts as an intermediary

-Fast shocks in hot low density gas→ Slow shocks in dense molecular gas

How is H_2 temperature maintained?

-H_2 cooling time is only ~10^4 yr

-Jet breakout in ~10^6 yr

-Jet lifetime is ~10^7 yr

-ISM turbulence may serve as a reservoir of K. E.

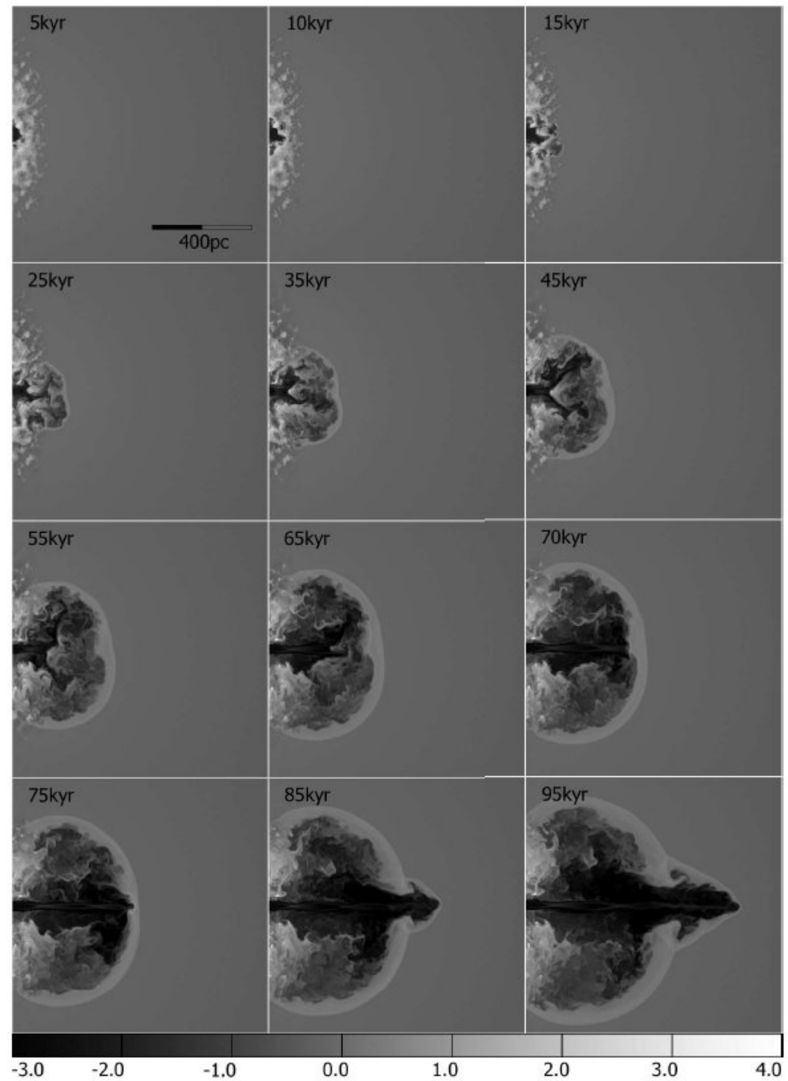
-Cloud collisions may continually reheat gas.

Is H_2 formed in stationary or outflowing gas?

Image credit: 3C 321 X-ray, opt., radio; D. Evans, NASA/CXC/STScI/VLA

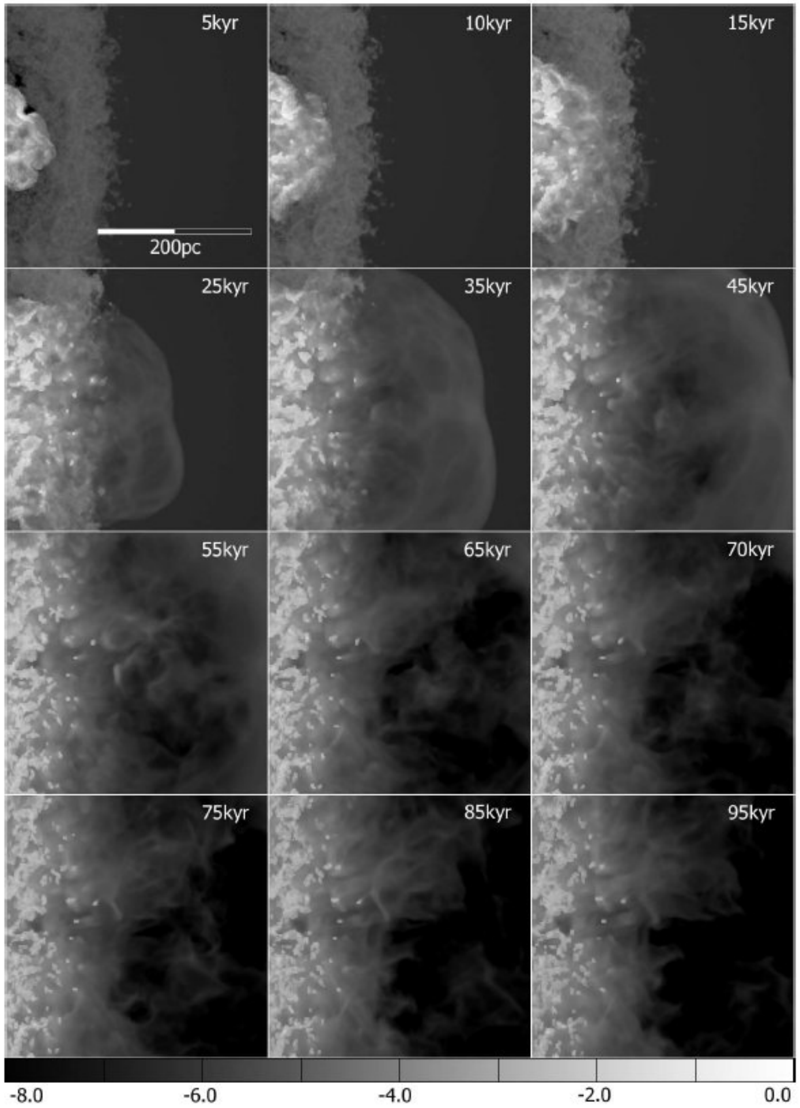
Jet-ISM Interaction

- Sutherland 07
  Jet-disk interaction:
  Gas density image
- 3 stages:
  - Spherical expansion (15 kyr)
  - Multi-channel flow (30-60 kyr)
  - Jet breakout (90 kyr)
- Jet couples strongly to clumpy ISM disk over 4π sr

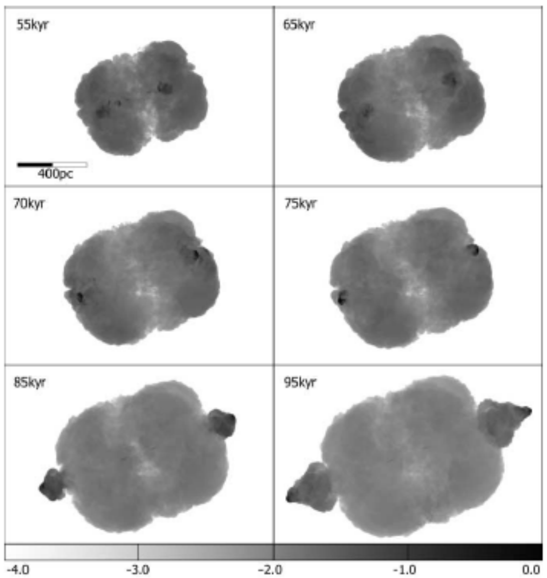


Jet-ISM Interaction

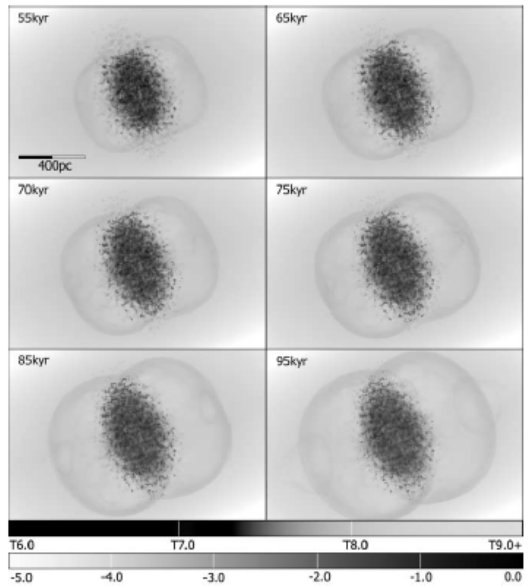
- Sutherland 07:
  X-ray emissivity
- Kpc atomic disk shock-heated from inside out (0-50 kyr)
- Heating continues after jet breakout
- High density massive clumps shock-heated but not destroyed or accelerated
- Lower density gas is uplifted or ablated
- Atomic outflow/wind



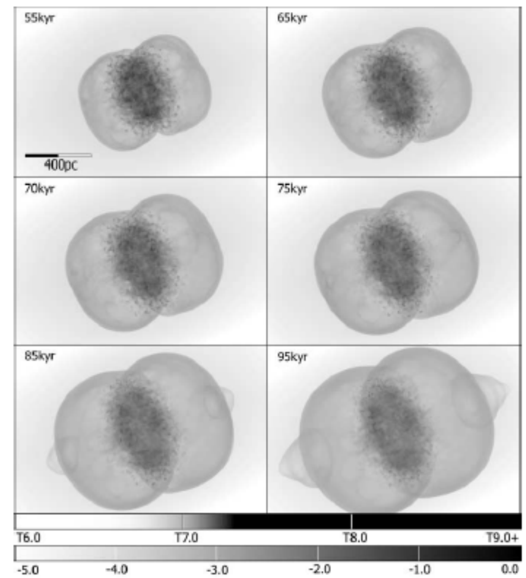
Jet-ISM: multiwavelength view



Radio



Soft X-ray



Hard X-ray

- Sutherland 07 jet-disk interaction: ***simulated Radio and X-ray images***
- Synchrotron from jets/lobes
- Soft thermal X-ray emission from disk
- Hard X-rays from jet bubble cavities

Jet-Driven Outflows

Neutral and ionized outflows (1-2×10^3 km s^{-1}) found in several radio MOHEGs

-We observed 8 radio galaxies with neutral (H I) outflows:
100% of them show strong H_2 emission and large H_2 /PAH7.7
(Guillard 11, Morganti 05)

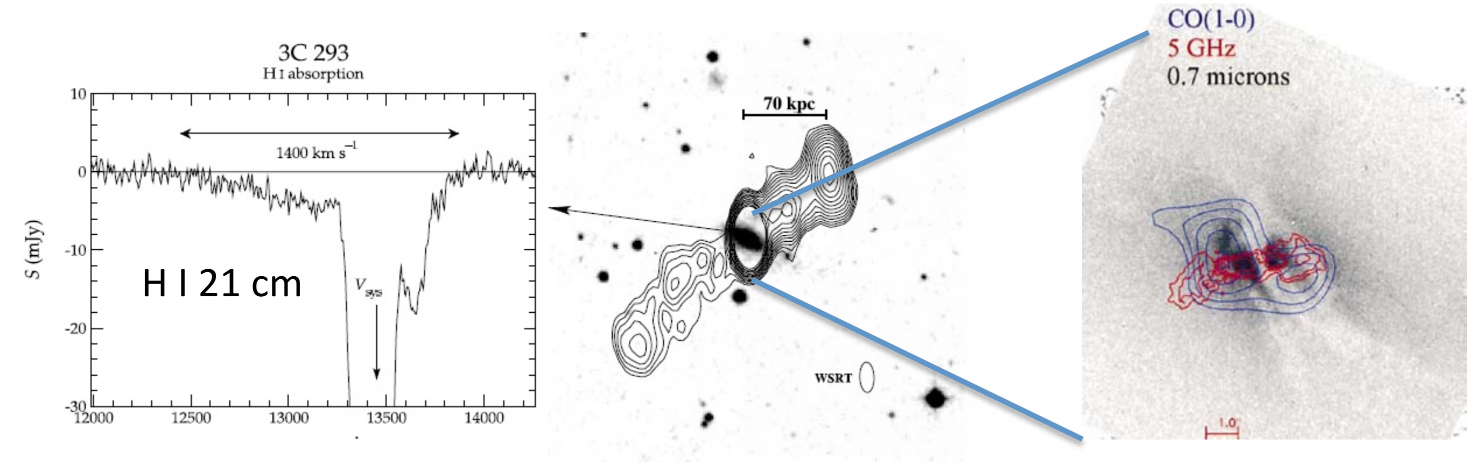
- 3C 326 shows a neutral (Na I D) outflow (1800 km s^{-1}, 35 $M_\odot$ yr^{-1})
(Nesvadba 10)

-Ionized (O II) gas outflows (e.g., 3C 293, 4C 12.50, PKS 1549)
(Emonts 05, Holt 08, 10)

-Are molecular outflows present?

Image credit: M84 (3C 272.1) X-ray, opt., radio; R. Laing, CXC/ESO/VLA

3C 293 Jet-Driven Outflow



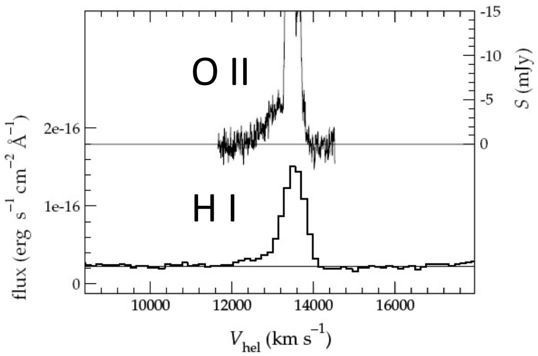


Figure 10. [O II] emission line in region E0 and H I absorption profile (inverted) plotted in one image.

•1000 km s^{-1} H I (20 $M_\odot$ yr^{-1}), ionized (0.1 $M_\odot$ yr^{-1}) outflows (Morganti 03; Emonts 05).

•M(**H_2** cold, warm)=1.5×10^{10}, 4×10^{9} $M_\odot$ (A. Evans 99, Ogle 10)

…Stay tuned for 70 ks Chandra X-ray image (Ogle 11).

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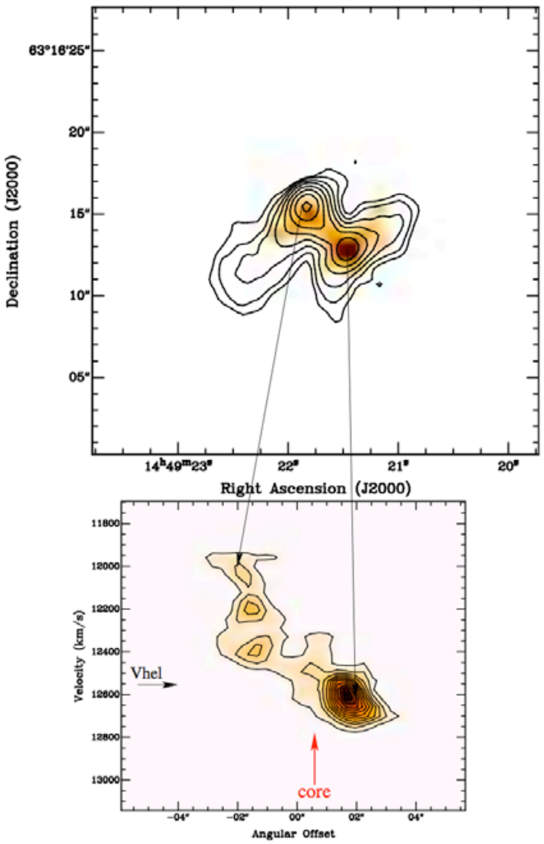
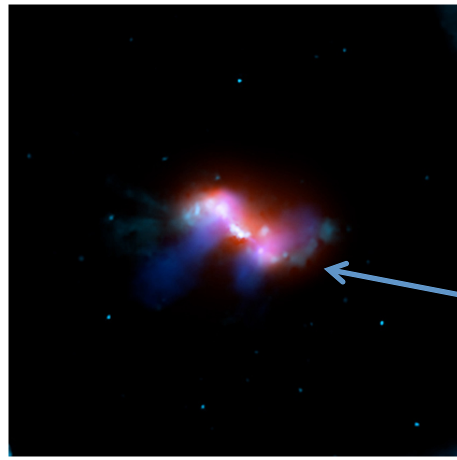
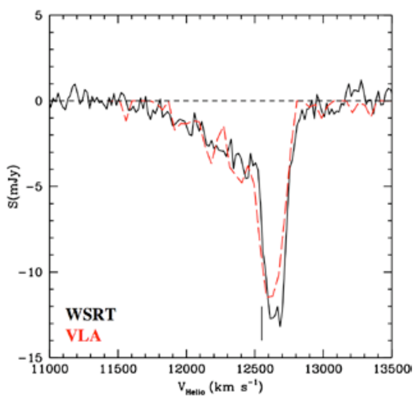
3C 305 Jet-Driven Outflow







•800 km s^{-1} H I (20 $M_\odot$ yr^{-1}) outflow driven from NE radio lobe (Morganti 05).

•Soft X-ray emission (red) coincident with optical [O III] (green) extends beyond radio lobes (blue). Shocked or photoionized? (Massaro 09)

•M(**H_2** warm)=1.5×10^{10},4×10^{9} $M_\odot$ (Guillard 11)

Molecular Diagnostics with Herschel

Recent Herschel PACS OH + ground-based CO observations have highlighted the importance of ***molecular outflows*** in lo-BAL QSO/ULIRG Mrk 231 (Fischer 10, Feruglio 10).

Inferred outflow rate (2000 $M_{\odot}$ yr^{-1}) is 10× larger than the SFR, indicating that star formation will be quenched in <10^7 yr.

CO spectral line energy distribution (SLED) measured with SPIRE suggests that CO might be heated by X-rays from the AGN (van der Werf 10)…

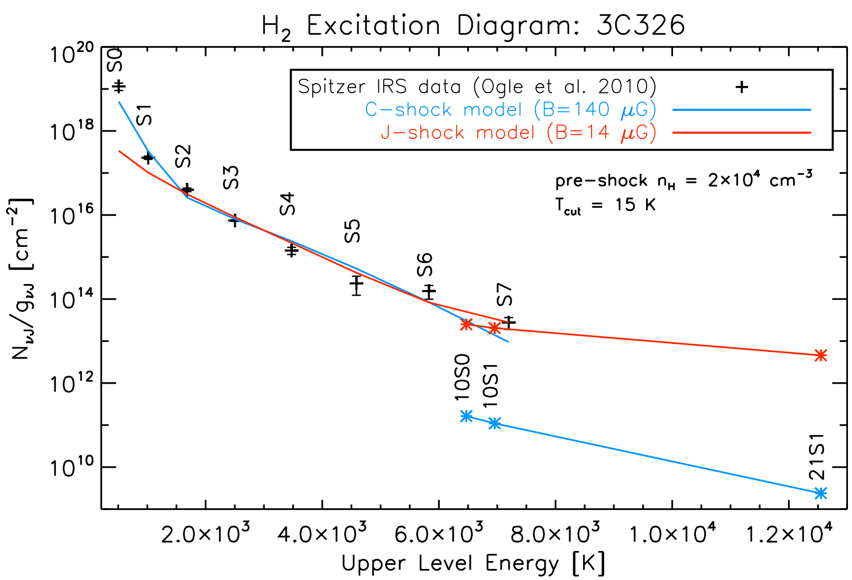
…However shock-heating by the BAL outflow or radio jet might be more important.

Luminous H_2O+ and OH+ emission also demonstrate the importance of X-ray or shock-driven molecular chemistry (van der Werf 10)

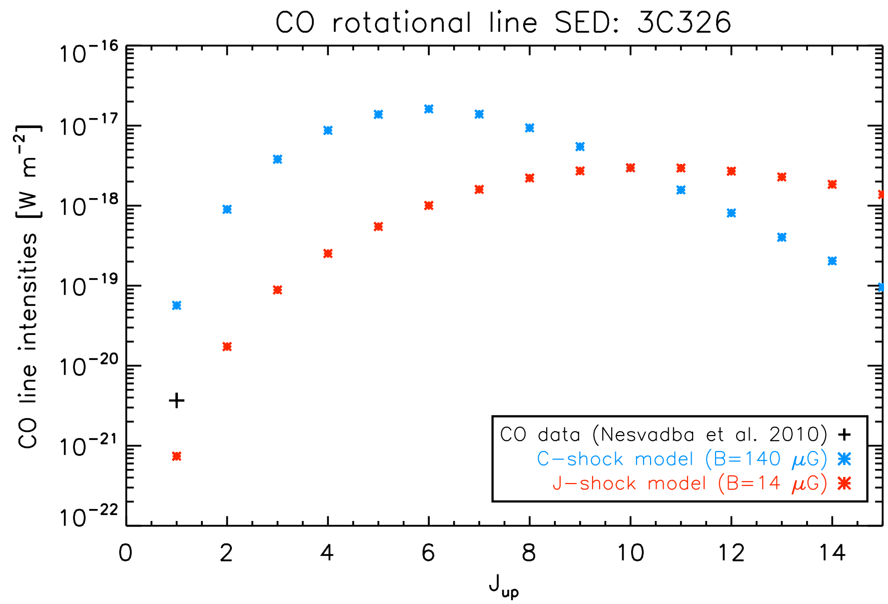
Image credit:Mrk 231, ESA/STSci

3C 326 H_2 and CO Shock-Excitation

Observed+Model H_2



Predicted CO

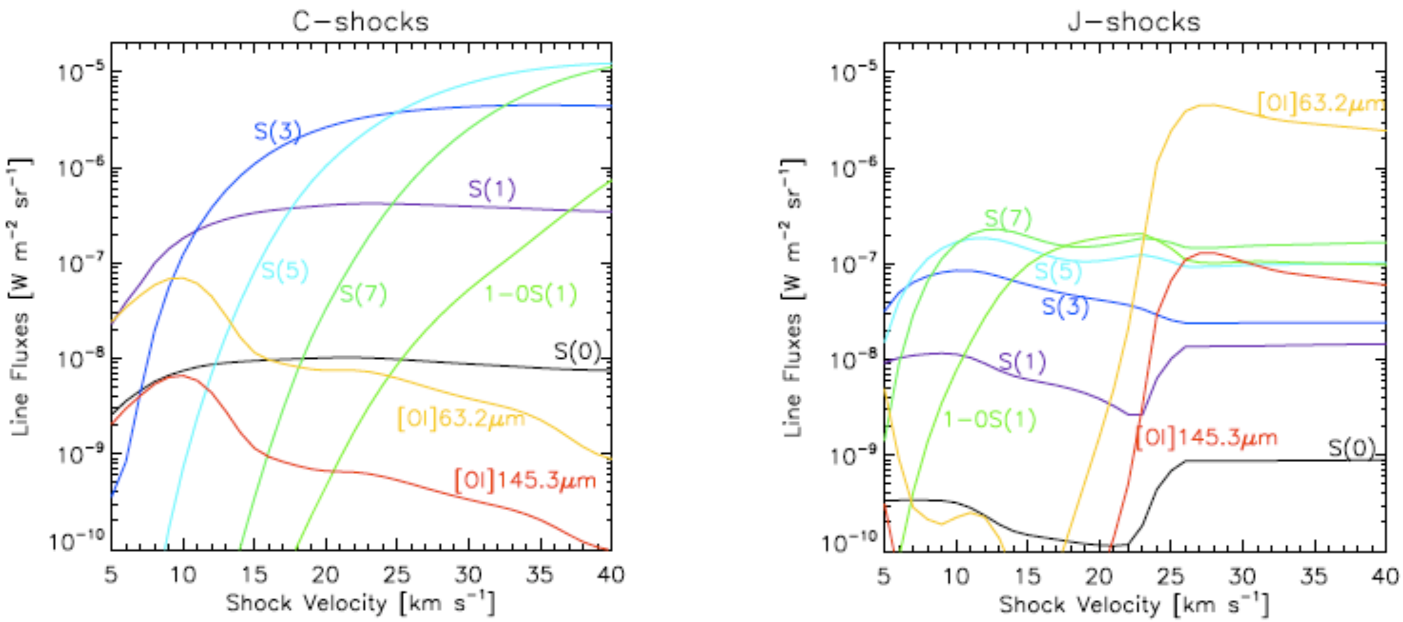


- Low-J rotational $\mathbf{H_2}$ modeled by C-type shocks (Guillard 11b)

- Our Palomar observations of **rovib** $\mathbf{H_2}$ indicate a strong J-shock component.

- Our proposed Herschel SPIRE CO spectra of radio MOHEGs will test shock models.

[O I] Emission from Shocks



•[O I] 63 μm emission line is strong in slow C-shocks and fast J-shocks (Guillard 09 PhD thesis)

•Our proposed Herschel PACS [O I] spectra of radio MOHEGs will further test shock models and probe an important cooling channel.

Summary and Future

•H_2 emission probes warm molecular gas shocked by the radio jet

• AGN radio feedback can dramatically disturb the molecular and atomic ISM.

•Neutral and ionized atomic outflows may be driven by radio jets.

-Are there molecular outflows too?

•Star formation efficiency is suppressed in radio galaxies.

•Future molecular and atomic line spectroscopy with Herschel SPIRE and PACS will further probe the jet-ISM interaction.

Image credit: Hydra A (3C 18) X-ray, opt., radio; C. Kirkpatrick, CXC/CFHT/DSS/VLA