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Jet Feedback on the Interstellar Medium of the Radio Galaxy 3C293

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Abstract

We present a **70 ks *Chandra* observation** of the radio galaxy **3C 293**. This galaxy belongs to the class of molecular hydrogen emission galaxies (MOHEGs) that have very luminous emission from warm molecular hydrogen, heated by jet-driven shocks. Exactly how this mechanism works is still poorly understood. With *Chandra*, we observe X-ray emission from the jets within the host galaxy and along the 100 kpc radio jets. We model the X-ray spectra of the nucleus, the inner jets, and the X-ray features along the extended radio jets. Both the nucleus and the inner jets show evidence of 10^7 K shock-heated gas. The kinetic power of the jets is more than sufficient to heat the X-ray emitting gas within the host galaxy. The thermal X-ray and warm H_2 luminosities of 3C 293 are similar, indicating similar masses of X-ray hot gas and warm molecular gas. This is consistent with a picture where both derive from a multiphase, shocked interstellar medium (ISM). We find that radio-loud MOHEGs that are not brightest cluster galaxies (BCGs), like 3C 293, typically have $L_{H2}/L_X \sim 1$ and $M_{H2}/M_X \sim 1$, whereas MOHEGs that are BCGs have $L_{H2}/L_X \sim 0.01$ and $M_{H2}/M_X \sim 0.01$. The more massive, virialized, hot atmosphere in BCGs overwhelms any direct X-ray emission from current jet-ISM interaction. On the other hand, $L_{H2}/L_X \sim 1$ in the Spiderweb BCG at z=2, which resides in an unvirialized protocluster and hosts a powerful radio source. Over time, jet-ISM interaction may contribute to the establishment of a hot atmosphere in BCGs and other massive elliptical galaxies.

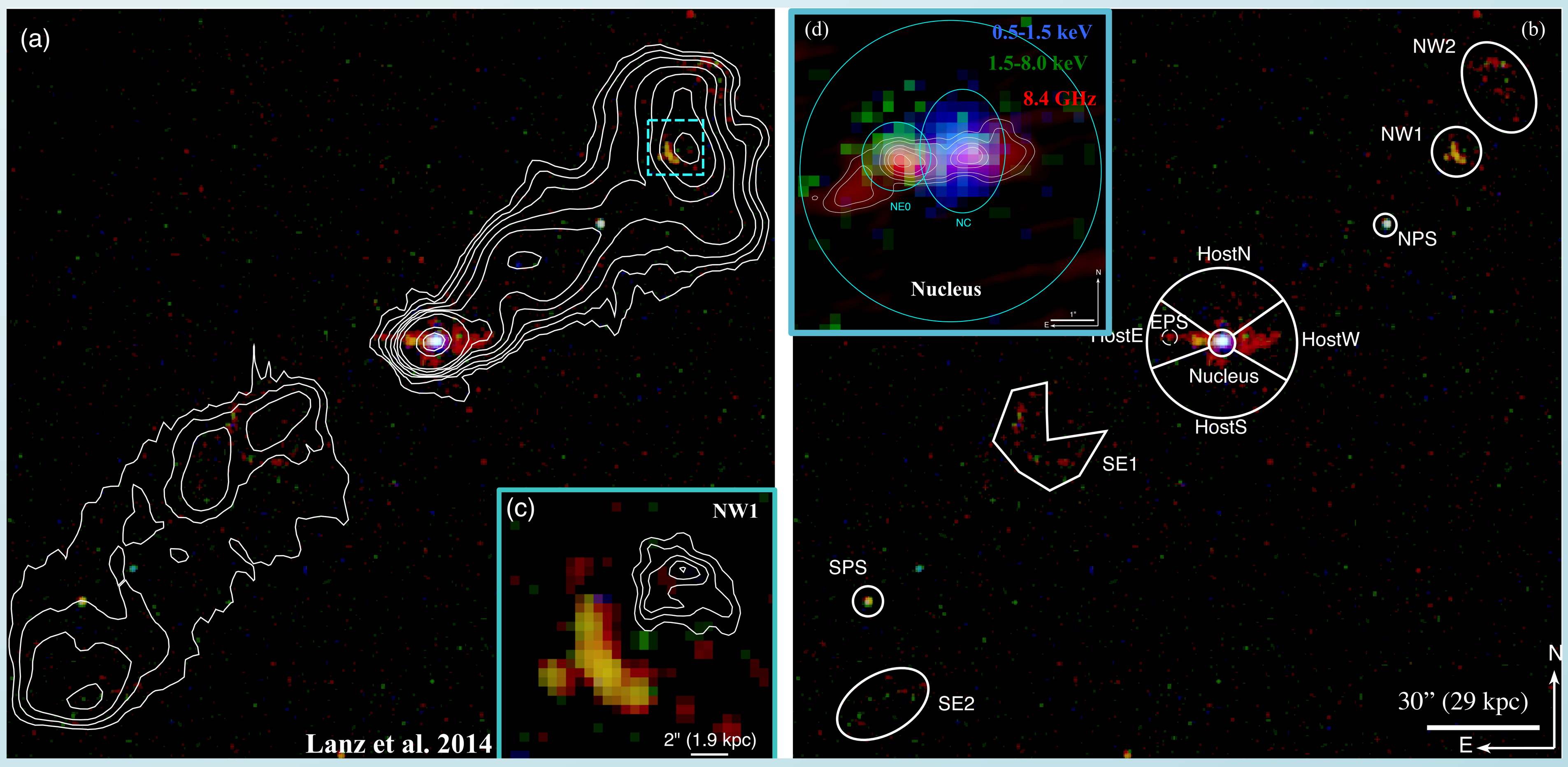


Fig. 1 Chandra images of 3C293 showing soft (0.5-1.5 keV), medium (1.5-3.0 keV) and hard (3-8 keV) emission overlaid with 1.4 GHz contours (a, c) and spectral apertures (b). (c) has higher resolution 1.4 GHz contours of the NW jet hotspot, which may be associated with NW1. (d) shows the nucleus, which has a softer source to the East of the AGN that is coincident with a knot in the small radio jet.

X-ray Emission in 3C293

Figures 1 and 2 show the Chandra image of 3C293 and its relation to the large and small radio jets. We extracted and modelled the X-ray spectra for the regions shown in Fig. 1b with more than 100 counts (Nucleus, Host, NW1, NW2, and SE1). We describe each below:

- **Nucleus (Fig. 1d)**
  - **Central hard source (NC)**
    Most likely the AGN with a $L_{2\text{-}10\,keV}$ of 7×10^{42} erg s^{-1} behind $N_H = 9 \times 10^{22}$ cm^{-2}
  - **Softer off-nuclear source (NE0)**
    Contains ~10% of the nuclear counts and is coincident with E0, a knot of bright optical and radio emission associated with the launch site of the ionized outflow
- **Jet-like Emission in Host Galaxy (Fig. 1 and 2)**
  The brightest X-ray emission outside the nucleus is dominated by soft X-rays and primarily extends EW from the nucleus, roughly in the directions of the small radio jets.
- **Diffuse Emission in Host Galaxy (Fig. 1 and 2)**
  Diffuse X-ray emission is also found North and South of the nucleus. The total X-ray emission within the host, excluding the AGN, is 2×10^{41} erg s^{-1}.
- **A Possible Hot-Spot at NW1 (Fig. 1c):**
  NW1 is detected with 120 counts and is likely synchrotron emission that may be associated with the radio hot-spot shown in detail in Figure 1c. The separation between the X-ray and radio peaks is 6.6 kpc; similar offsets have been seen in other radio galaxies (e.g. in 3C 390.3 by Hardcastle et al. 2007), plausibly explained by the aging of synchrotron-emitting electrons.
- **Possible Shock-caps at SE1 and NW2 (Fig. 1)**
  - **SE1**
    SE1, detected with 110 counts, is a curve of mostly soft emission that falls between two brighter regions of radio emission, suggesting this feature may lie at the forefront of an ejection burst, perhaps associated with a bowshock. SE1's morphology also has similarities with the thermal cap on the inner southern lobe of Cen A (Kraft et al. 2009), and it is well fit with a thermal model.
  - **NW2**
    The end of the NW jet is detected with 100 counts. Like SE1, its morphology is similar to the cap on Cen A's southern lobe, but it is better fit with a power law.
- **A Tentative Detection of the End of the SE jet (SE2 in Fig. 1)**
- **Three points sources (NPS, SPS, and EPS in Fig. 1)**

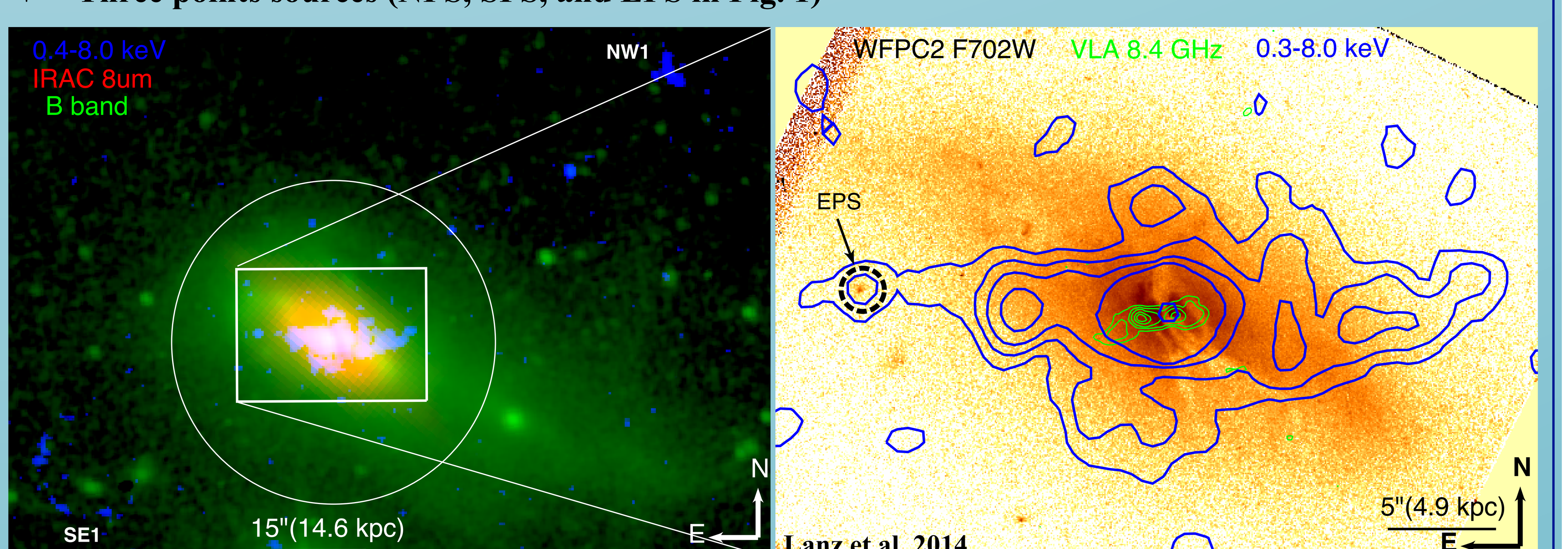


Fig. 2 X-ray emission extends through most of the host galaxy's optical emission and past the bulk of the MIR. A clear dust lane is visible over the nucleus and the features along the large jets (NW1 and SE1) are beyond the host galaxy and not in its tidal debris.

Jet-driven Shocks Heat ISM to Power X-ray and H_2 Emission in Radio MOHEGs

The kinetic power of jets in 3C 293 (3×10^{43} erg s^{-1}) is more than sufficient to power the X-ray thermal emission and the warm H_2 emission as well as driving both the ionized and neutral outflows found in 3C 293. Fig. 3 summarizes the picture of the way in which the jet impacts the ISM. As the jet traverses its host galaxy, it heats the diffuse ISM, inflating a hot cocoon and driving shocks into the entrained and ambient molecular gas. The shear between the hot gas and the molecular clouds may power the H_2 emission through turbulent mixing layers (e.g. Guillard et al. 2009). Fig. 5 compares the H_2 and diffuse X-ray luminosities of different types of MOHEGs. For radio MOHEGs, where both luminosities are thought to be powered by the dissipation of mechanical energy of the jet, we typically find $L(H_2)/L_X \sim 1$, consistent with the scenario presented. The shocks may also be enhancing CO emission (supported by the highly excited CO emission found by Papadopoulos et al. [2008]), which may explain the high gas-to-dust ratio we observe in 3C 293 and has been seen in other MOHEGs including NGC 4258 (Ogle et al. 2014) and the Taffy bridge (Zhu et al. 2007). It has recently been shown in 3C 326N (another MOHEG) that the dissipation of this turbulent energy can maintain the H_2 on timescales of $\sim10^7$ yr, about 10^3 times the cooling timescale of the warm H_2, enough to maintain it between cycles of jet activity (Guillard et al. 2014).

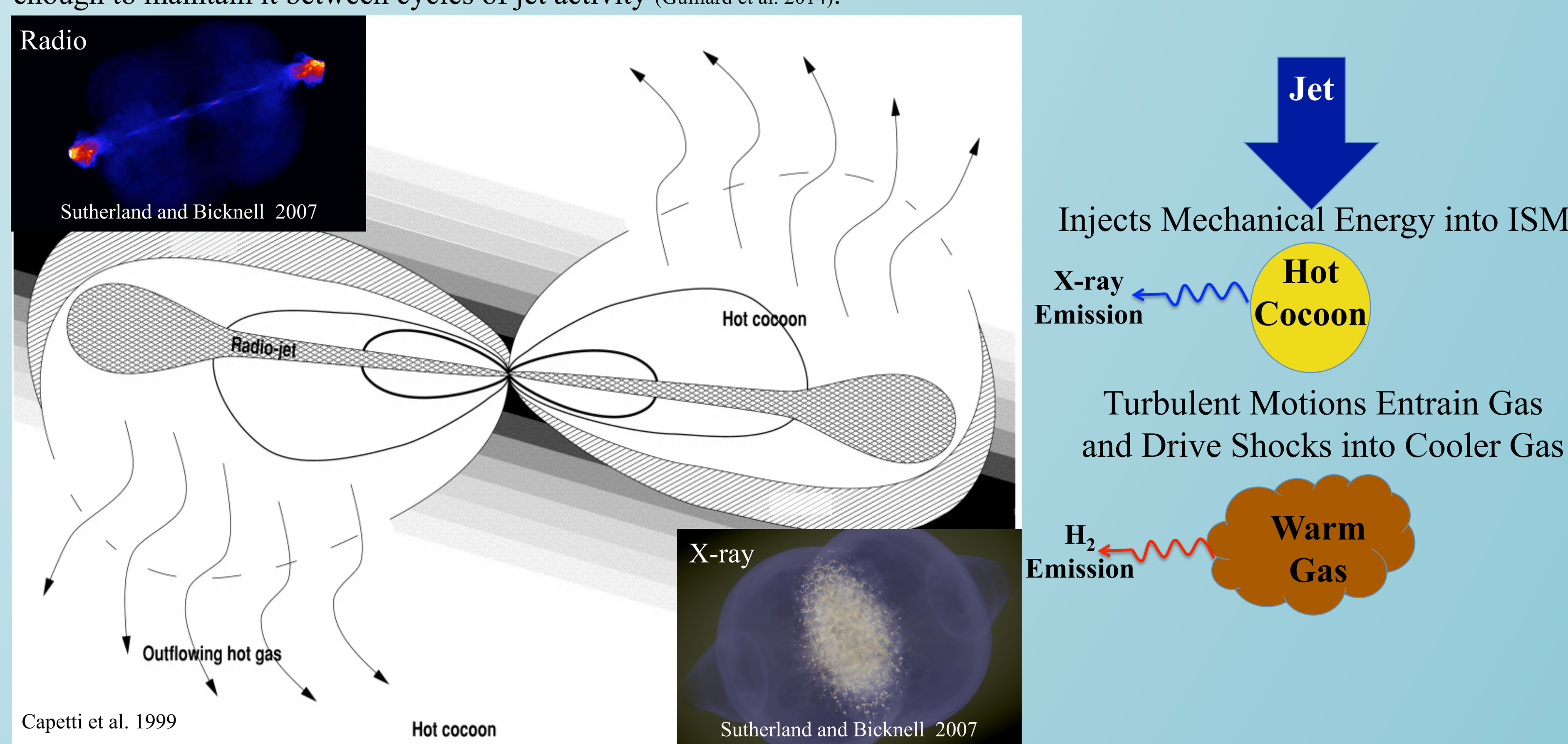


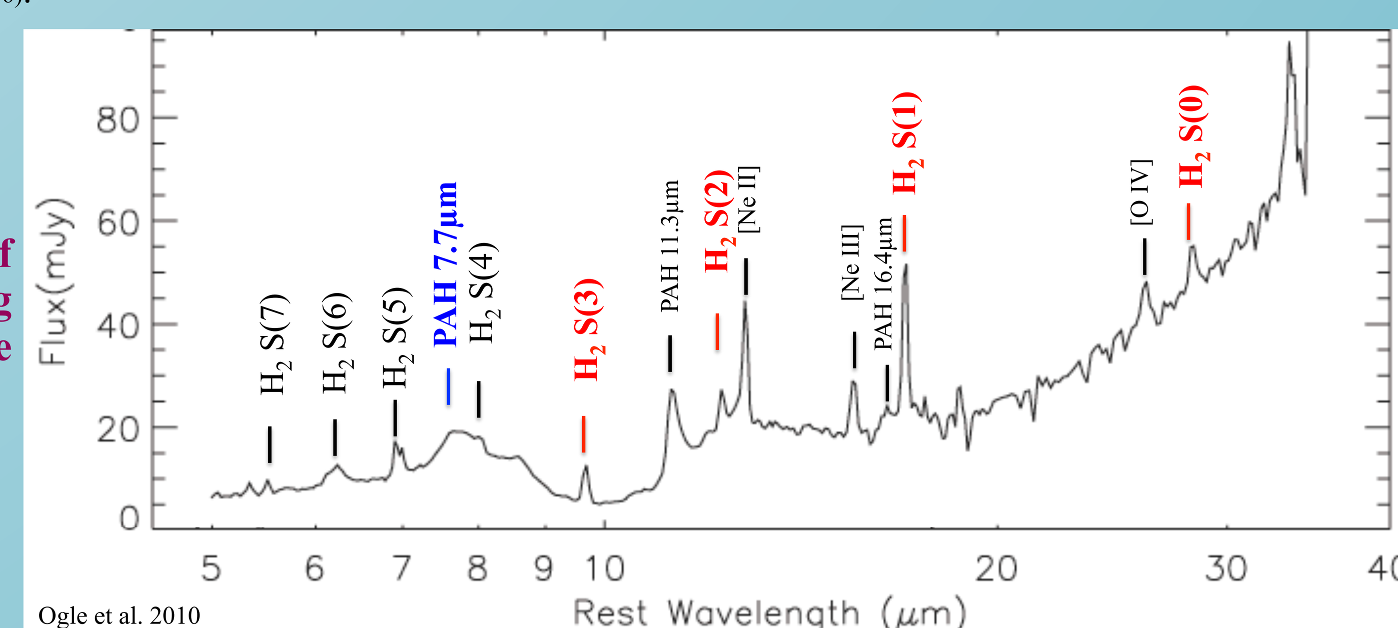
Fig. 3 Schematics illustrating the scenario likely taking place in 3C 293, wherein the radio jet inflates of a hot, X-ray emitting cocoon. This cocoon can then carry the effects of the jet to much more of the galaxy than the jet cross-section. Turbulent motions in the cocoon can entrain cooler gas and drive shocks that power the H_2 emission. A snapshot of a simulation (Sutherland & Bicknell 2007) imaged in the radio and X-ray support the plausibility of this mechanism.

What is a MOHEG?

MOHEGs are Molecular Hydrogen Emission Galaxies, which were discovered with *Spitzer* and showed strong rotational lines of H_2 (0-0). Based on the high H_2/7.7μm PAH ratio (Fig. 4), the H_2 emission cannot be powered by UV photons from young stars which would also excite the PAH molecules. Direct heating by the AGN is also unlikely, since $L_{H2}/L_{2\text{-}10keV}>0.01$ (Ogle et al. 2010). The likely heating mechanism is dissipation of kinetic energy through shocks or cosmic rays. MOHEGs are found in radio galaxies (Ogle et al. 2010), brightest cluster galaxies (Egami et al. 2006), luminous IR galaxies (LIRGs, Lutz et al. 2003), and colliding galaxies (Appleton et al. 2006).

Fig. 4

Spitzer IRS Spectrum of 3C293 showing strong emission of H_2, indicative of a MOHEG.



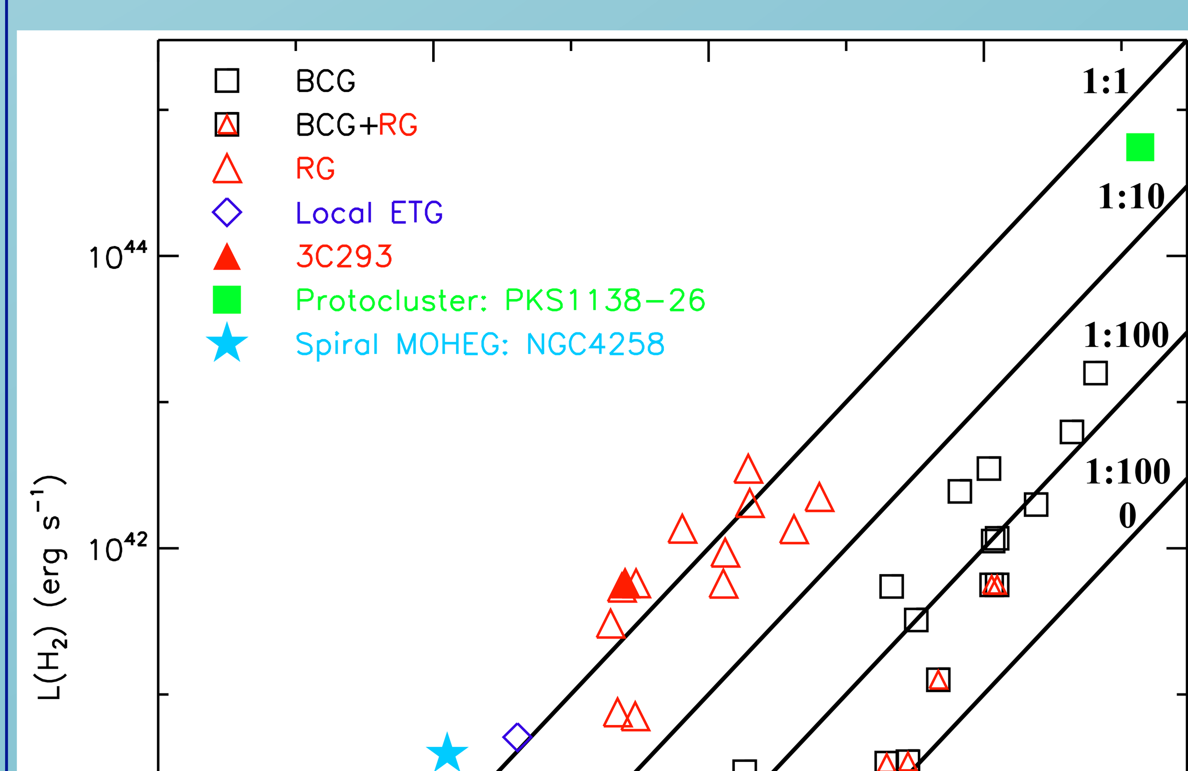


Fig. 5 H_2 luminosity of MOHEGs compared to the X-ray luminosity of the host galaxy, excluding the AGN. Radio galaxies have generally have similar $L(H_2)$ and L_X, with higher L_X than early type galaxies. A ratio of $L(H_2)/L_X \sim 1$ in radio galaxies is consistent with a picture that both are powered by the dissipation of mechanical energy from the jet. **Brightest cluster galaxies** have X-ray luminosity associated with their cluster within the host galaxy, so their $L_X \sim 100 \times L(H_2)$. The Spiderweb Galaxy (z=2), an intermediate case, is a strong radio source in an unvirialized protocluster.

References: Appleton, P. N., et al. 2006, ApJ, 639, L51; Carilli, C. L. et al. 2002, ApJ, 567, 781; Egami, E., et al. C. 2006, ApJ, 652, L21; Guillard, P. et al. 2009, A&A, 502, 515; Guillard, P. et al. 2014, arXiv:1410.6155; Hardcastle, M. J., Croston, J. H., & Kraft, R. P. 2007, ApJ, 669, 893; Kraft, R. P. et al. 2003, ApJ, 592, 129; **Lanz, L. et al. 2014, submitted to ApJ**; Lutz, D., et al. 2003, A&A,, 409, 867; Ogle, P., et al. 2010, ApJ, 724, 1193; Ogle, P., **Lanz, L.**, & Appleton, P. N. 2014, ApJ, 788, L33; Papadopoulos, P. P., et al. 2008, A&A, 491, 483; Sutherland, R. S., & Bicknell, G. V. 2007, ApJS, 173, 37; Zhu, M., et al. 2007, AJ, 134, 118