Shock heating by nearby AGN

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1 Abstract

Shock heating by radio jets is potentially an important process in a range of environments as it will increase the entropy of the heated gas. Although this process is expected to occur in the most powerful radio-loud AGN, strong shocks have so far only been detected in nearby low-power radio galaxies. Here we discuss X-ray detections of strong shocks in nearby galaxies, including a new detection of shocked gas around both lobes of the nearby radio galaxy NGC 3801 with inferred Mach numbers of 3 – 6 and a total injected energy comparable to the thermal energy of the ISM within 11 kpc. We discuss possible links between shock heating, AGN fuelling and galaxy mergers and the role of this type of system in feedback models.

2 When and where is shock heating important?

All radio-loud AGN, whatever their radio luminosity and eventual morphology, are expected to go through an initial phase of supersonic expansion before coming into pressure balance (see, for example, [1]). The length of this phase, the amount of energy injected into the external medium during this phase, and the location of the energy injection depend on the jet power and density of the environment. In a poor environment, the radio source will remain overpressured for longer, so that the shock heating phase will be longer lived. It therefore seems likely that the two places where shock heating will be easiest to detect are in the poorest environments, and in the environments of the most powerful AGN. Indeed, the first (and until recently only) direct detection of radio-galaxy shock heating was in the galaxy halo of the nearest radio galaxy Centaurus A [2], which has a low radio luminosity and FRI morphology, but whose inner lobes are still in the supersonic expansion phase (see Section 3).

More recently weak shocks have been detected in the cluster environments of several more powerful radio galaxies, e.g. M87 [4], and the FRII sources Cygnus A [3, 5] and Hydra A [6]; however, there remains no convincing case of a strong shock associated with an FRII radio galaxy. In addition, FRII radio galaxies for which measurements exist of both the internal pressure (via lobe inverse Compton emission) and the external pressure appear to be close to pressure balance rather than strongly overpressured [7, 8, 9], so that lobe expansion is not likely to be highly supersonic. While it is not possible to rule out an important role for strong shocks produced by powerful radio galaxies, the observational evidence suggests that it is in the early stages of radio-source evolution, for both FRI and FRII sources, that shock heating is most important. Although the main emphasis of most work on radio-source impact has been on the group and cluster scale effects of radio galaxies, the impact of shock heating on the ISM of AGN host galaxies is likely to be dramatic, as we demonstrate below.

In the following sections we review the first detection of radio-source shock heating in Centaurus A before presenting a new example of strongly shocked gas shells in the ISM of NGC 3801 that share some characteristics with Cen A but also show some important differences. Finally, based on the nuclear properties and host galaxy characteristics of systems with detected strong shock heating, we discuss the links between shock heating and AGN fuelling and possible implications for the role of shock heating in feedback models.

3 Cen A and NGC 1052

Kraft et al. (2003) [2] detected a bright shell of hot gas surrounding the south-west inner lobe of the nearest radio galaxy Centaurus A. Fig. 1 shows more recent *Chandra* data [10] illustrating the sharp X-ray shell. The shell has a temperature ten times higher than that of the surrounding interstellar medium, and the total thermal energy of the shell is a significant fraction of the energy of the ISM. Centaurus A has an FRI morphology, so would traditionally have been expected to have subsonically expanding lobes; the detection of strongly shocked gas in this system has highlighted the fact that energy input via shocks is likely to be important in the early stages of expansion for all types of radio galaxies.

NGC 1052 is another nearby galaxy where it has been suggested that the small radio source could be shocking and heating its hot ISM [11, 12]. A recent, deep *Chandra* observation reveals in detail the radio-related X-ray structure hinted at by the earlier snapshot observation, but does not show clear evidence for shocked shells, suggesting that the radio-source/environment interaction in this system may be considerably more complex than the shock heating seen in Cen A.

4 A new detection of shock heating in NGC 3801

Our recent *Chandra* observations of NGC 3801 [13] revealed a second definite example of strong shocks produced by a small FRI source on galaxy scales.

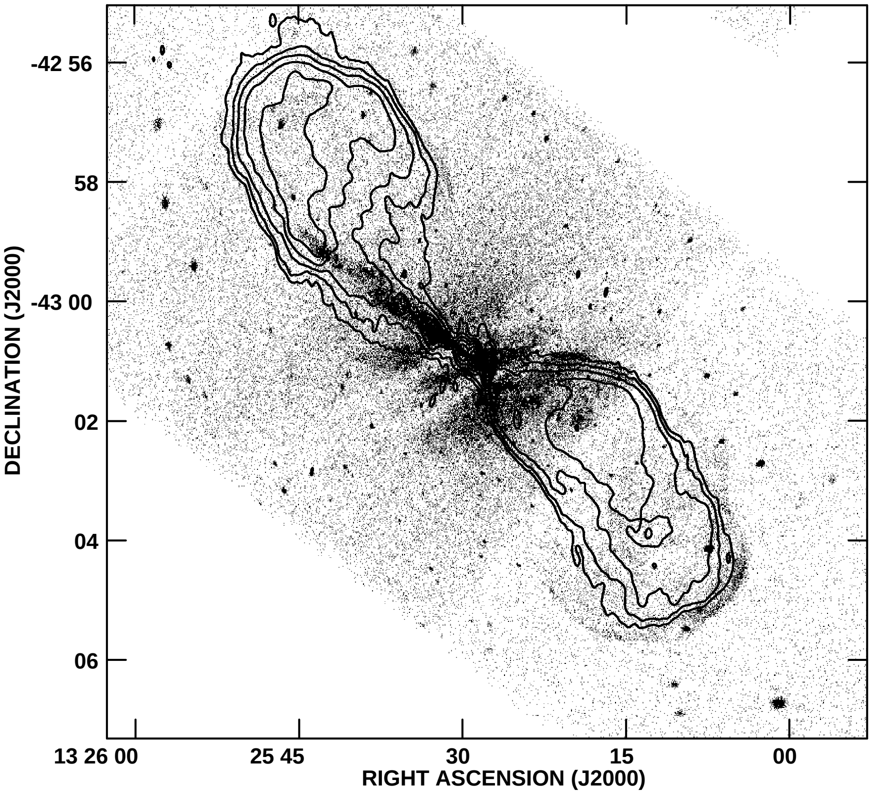

Fig. 1. The shell of shocked gas around the south-western lobe of Centaurus A as observed with *Chandra* [2, 10]. 20cm radio contours [17] are overlaid.

Fig 2 shows the *Chandra*-detected emission from NGC 3801, which traces well the outer edges of the radio lobes.

We can rule out a non-thermal model for the X-ray emission based on its spectrum, and find best-fitting *mekal* temperatures of 1.0 keV and 0.7 keV for the West and East lobes, respectively. The undisturbed interstellar medium has a temperature of 0.23 keV. We find that the observed density contrast is consistent with the value of 4 expected for a strong shock, using the mean properties of the shell and the ISM density halfway along the lobe. The shells are overpressured by a factor of 13 - 20 and the shell pressure is $\sim$ 7 times the synchrotron minimum internal lobe pressure (consistent with the general finding that FRI minimum pressures are typically an order of magnitude lower than external pressure [14, 15, 16]).

We estimated the shock Mach number using two methods, as descibed in more detail in [13]: applying the Rankine-Hugoniot jump conditions using the observed temperature jump gives $\mathcal{M} \sim 3 - 4$; alternatively, ram pressure

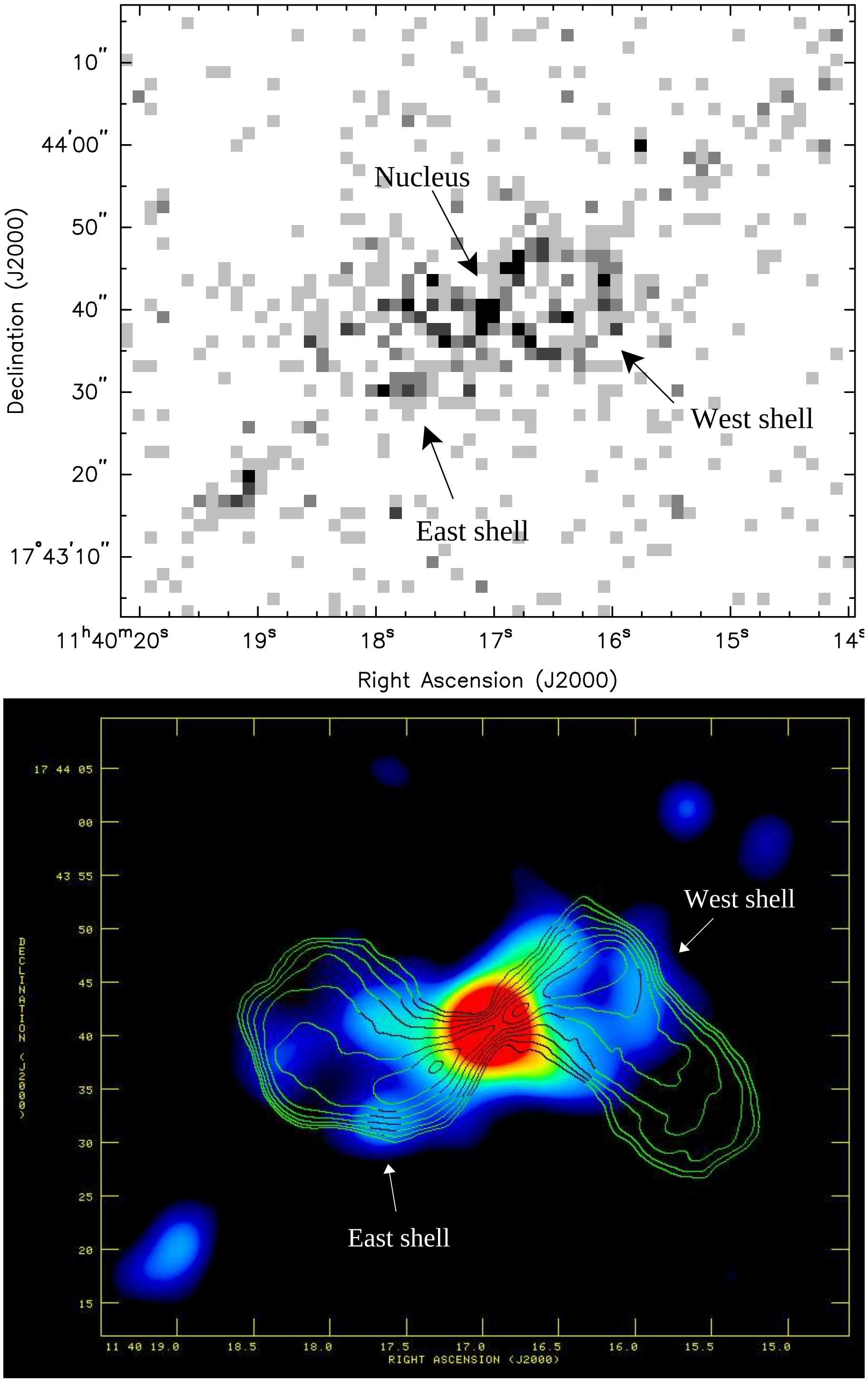

Fig. 2. The shocked gas shells of NGC 3801 as observed by *Chandra*. Top: binned 0.5 - 2 keV counts; bottom: Gaussian smoothed 0.5 - 2 keV image with 20 cm radio contours overlaid from new VLA data.

balance gives $\mathcal{M} \sim 5 - 6$. The discrepancy between the two methods is probably due to the expected temperature and density structure of the shell and the interstellar medium (in both cases the data are too poor to constrain these). Nevertheless this is a clear detection of strongly shocked gas with $\mathcal{M} \sim 3 - 6$, which implies a lobe expansion speed of $\sim 600 - 1200$ km s^{-1}.

The total thermal energy stored in the hot gas shells is $\sim 8 \times 10^{55}$ ergs, and for $\mathcal{M} \sim 4$, the total kinetic energy of the shells is $\sim 9 \times 10^{55}$ ergs. The total energy of the shells, 1.7×10^{56} ergs is comparable to $P_{int}V$, the approximate total energy available from the radio source as work; however, it is ~ 25 times the minimum work required to inflate the lobe cavities ($\sim 7 \times 10^{54}$ ergs), so that a simple calculation of the radio-source energy input from the cavity size would be a significant underestimate. The total energy is also equivalent to the thermal energy of the ISM within 11 kpc (or 25 percent of the thermal energy within 30 kpc). Shock heating is therefore the dominant energy transfer mechanism during this phase of radio-source activity, and will have dramatic long term effects: part or all of the ISM may be expelled from the galaxy, and the entropy of the gas will be permanently increased. The internal energy of the radio source ($\sim 4 \times 10^{56}$ ergs) must also eventually be transferred to the environment.

The age of the radio source in NGC 3801 is estimated to be $\sim 2 \times 10^6$ y from radio spectral ageing and dynamical arguments, which implies an energy injection rate of $\sim 3 \times 10^{42}$ ergs s^{-1}. This should correspond to a considerable fraction of the jet power, which is consistent with a rough estimate of its jet power based on scaling that of 3C 31 [18] by the ratio of radio luminosities of NGC 3801 and 3C 31. The rate of mechanical energy extracted is roughly an order of magnitude higher than the accretion-related X-ray luminosity, so that the AGN is more efficiently converting energy into jet production than radiation. We also find that the Bondi accretion rate from hot gas would be sufficient to power this radio outburst, for $\eta \sim 0.05$.

5 A link between shock heating and AGN fuelling?

Both Cen A and NGC 3801 are disturbed ellipticals with evidence for fairly recent mergers. Another property that the two sources have in common is that their nuclear X-ray spectra show a component of emission with heavy intrinsic absorption ($N_H > 5 \times 10^{22}$ cm^{-2} in both cases) as seen in high-excitation FRII radio-galaxy X-ray spectra [20]. This is in constrast to the vast majority of FRI radio galaxies, which possess no direct evidence for accretion-related X-ray emission or a torus [19, 20]. It is therefore interesting to speculate that these systems represent a particular class of FRI radio outburst fuelled by cold gas that may be driven into the centre during gas-rich mergers, a mechanism that is unlikely to operate in rich group or cluster-centre FRI radio sources. If this is true, then the shock heating process is not self-regulating, as most of the AGN energy goes into the hot phase of the ISM, so that the accretion rate of cold material is not directly affected. Cen A and NGC 3801 may represent a class of systems at the massive end of the galaxy luminosity function that experience extreme heating effects.

6 Conclusions

We have recently found a second example of strong shocks associated with the radio lobes of a nearby galaxy [13], with a total energy in the shock-heated shells ~ 25 times the minimum that would have been required to inflate the cavities subsonically: shock heating is therefore the dominant energy transfer mechanism for this source. Young radio galaxies should all go through an early stage of supersonic expansion, and the examples of Cen A and NGC 3801 show that this stage can have dramatic effects on the host galaxy ISM. As this stage is comparatively short-lived, and outbursts of the luminosity of NGC 3801 and Cen A are currently only detectable to $z \sim 0.04$ in the radio, further examples of this process may be difficult to find with current generation instruments; however, they are expected to be orders of magnitude more common than Cygnus A type radio outbursts. The nuclear and host galaxy properties of NGC 3801 and Cen A suggest that the shock heating in these galaxies may be directly related to their merger history; we suggest that merger-triggered radio outbursts could be an important galaxy feedback mechanism.

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