Building the Hot Intergalactic Medium in Galaxy Groups:

A *Chandra* view of Stephan's Quintet

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Motivation

The majority of galaxies in the Universe reside in galaxy groups, with the most common environment being spiral-rich groups similar to the Local Group (Eke et al. 2004). Mergers between such systems build more massive groups and clusters, and drive the development of their elliptical galaxy populations. Development of a hot intergalactic medium is linked to galaxy transformations - groups containing ellipticals are statistically more X-ray luminous, and the X-ray brightest groups all have dominant giant ellipticals (Mulchaey et al 2003). However, while we understand galaxy evolution relatively well, the origin of the extensive hot gas haloes of groups and clusters is as yet poorly known. Possibilities include accretion of primordial material, stellar winds and supernovae, and shock-heating of cool gas.

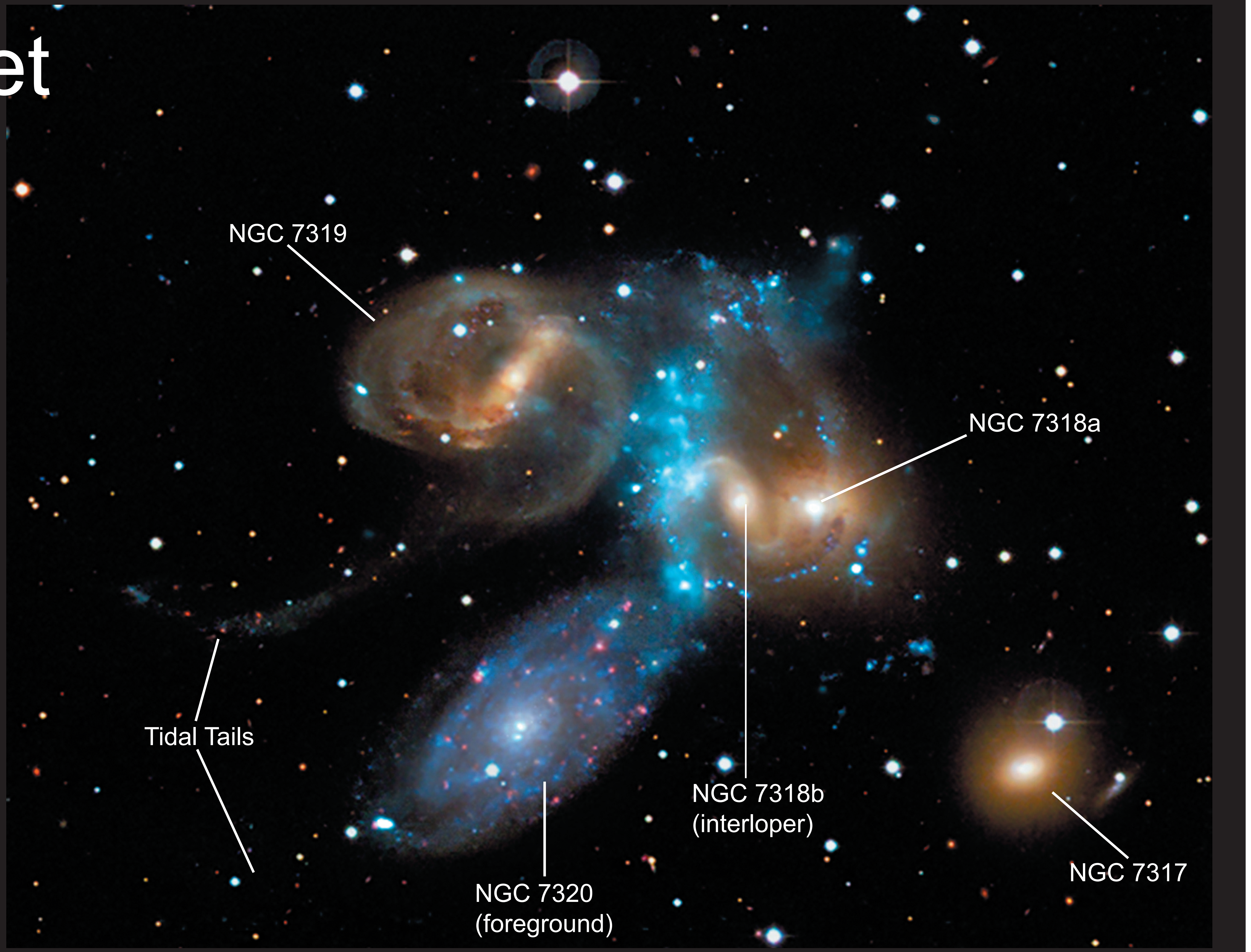
HCG 92 - Stephan's Quintet.

To examine this issue, we have selected a number of groups whose galaxy populations are in the process of merging and evolving. We present results form the first of these, Stephan's Quintet, which shows evidence of multiple galaxy interactions, tidal gas stripping and star formation, but which also hosts an extended hot halo (Sulentic et al. 2001). X-ray and radio observations also reveal a unique feature - a ridge of emission in the group centre which appears to be a shock, caused by a ~900 km s^{-1} collision between NGC 7318b and a massive filament of stripped HI.

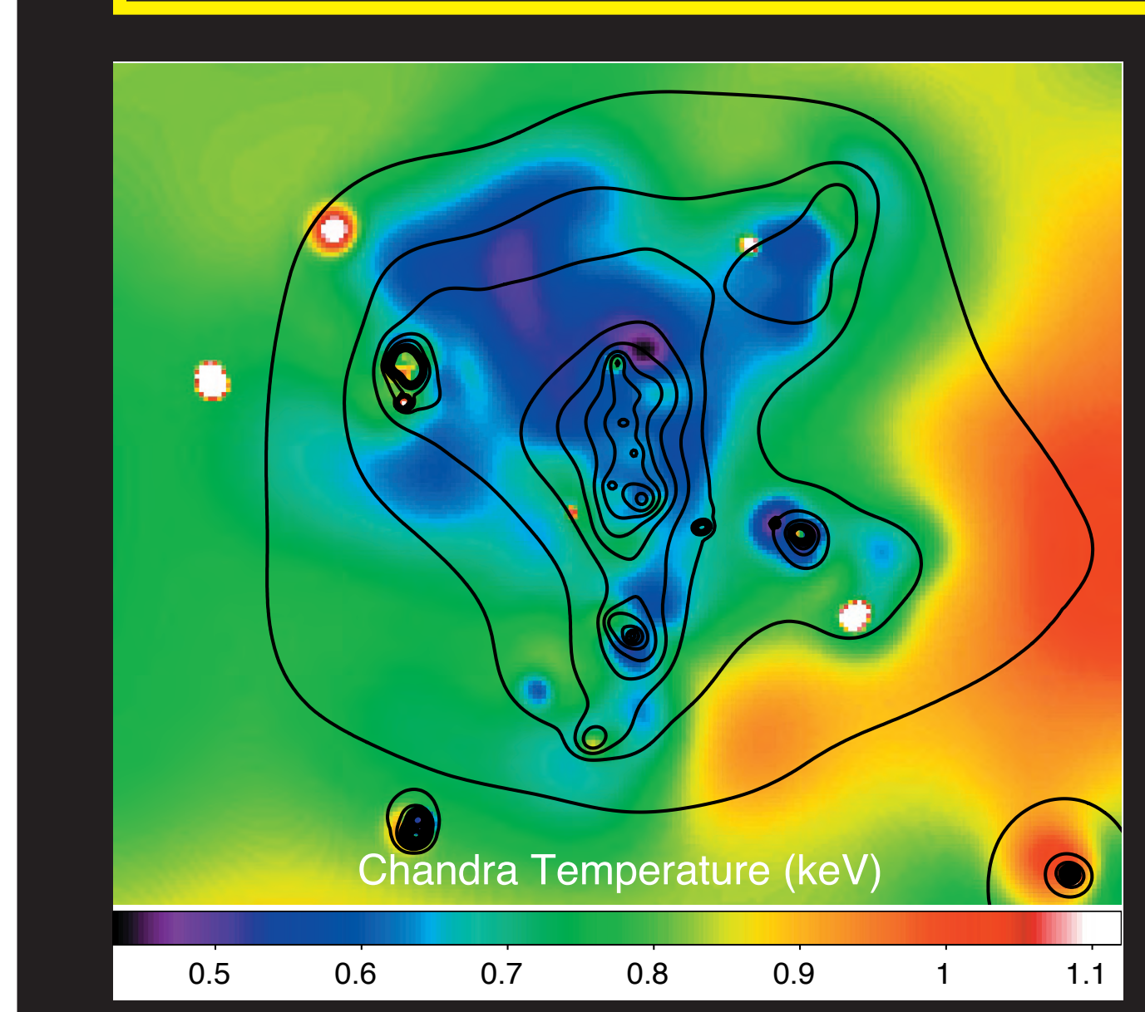
However, several questions remained unanswered:

1) Previous X-ray observations suggest the shock is cool (~0.6 keV, Trinchieri et al. 2005) - why is this?
2) How was the extended hot halo formed?
3) How does star formation affect the hot IGM, and what contribution does it make in the shock region?

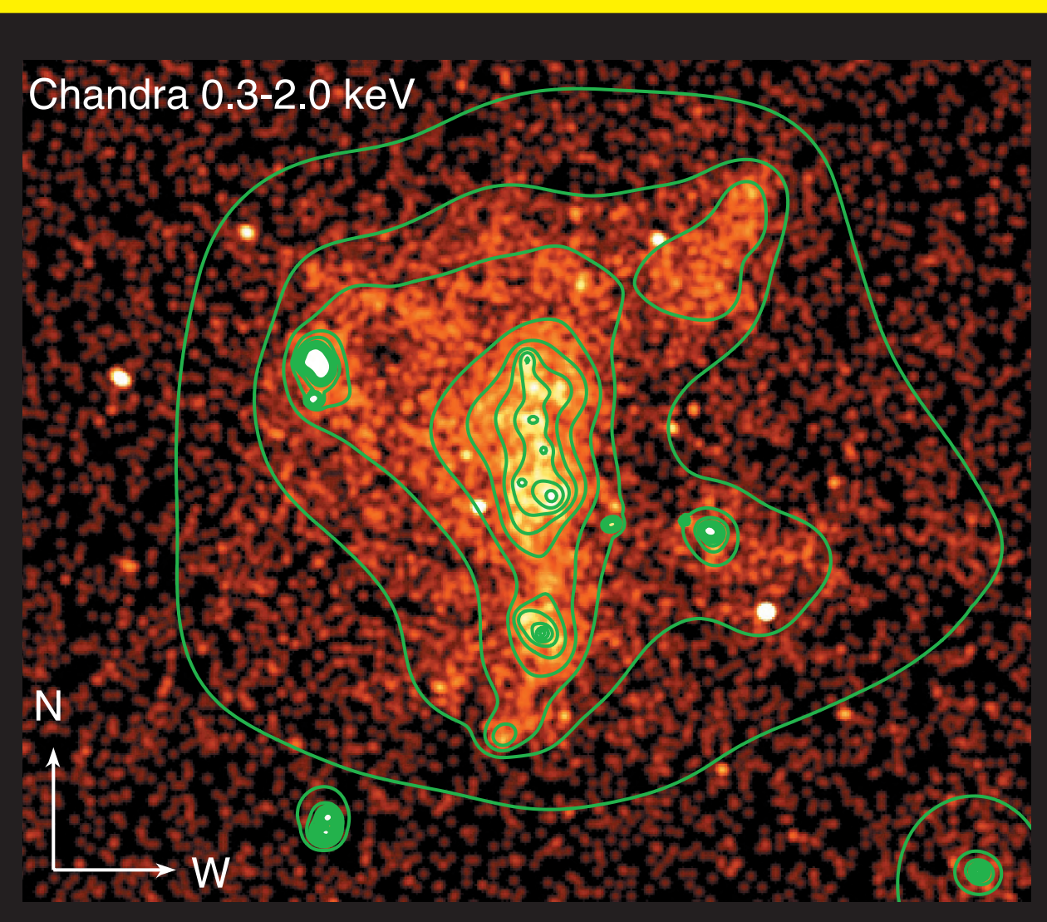
We use a deep ~95 ks *Chandra* observation, combined with GMRT 610 and 327 MHz data, to examine the group halo, galaxies and shock region.



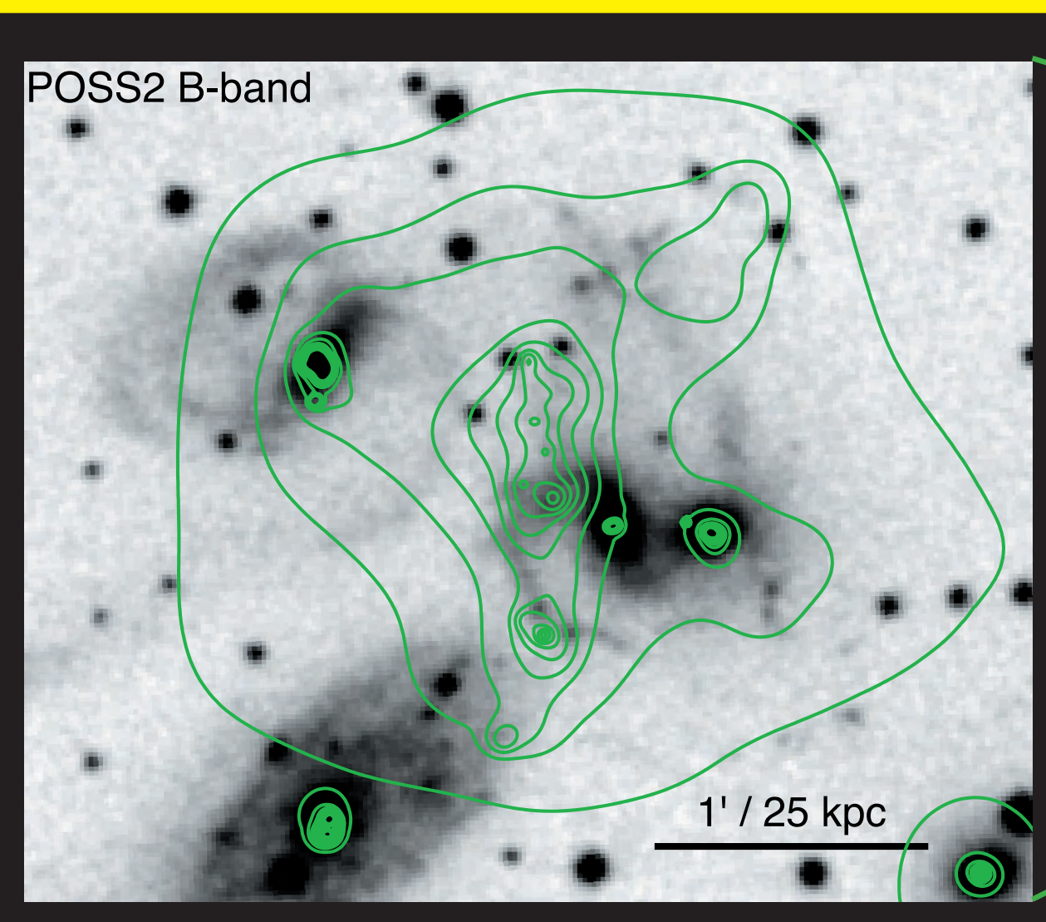
CFHT "true colour" optical image overlaid with *Chandra* adaptively smoothed 0.3-2.0 keV image (blue). NGC 7320 is a foreground spiral galaxy superimposed on the group. NGC 7318b has a collided with the group at a relative velocity ~900 km s^{-1}, creating an arc of shocked gas. Image c/o Eli Bressert (C.f.A., University of Exeter).



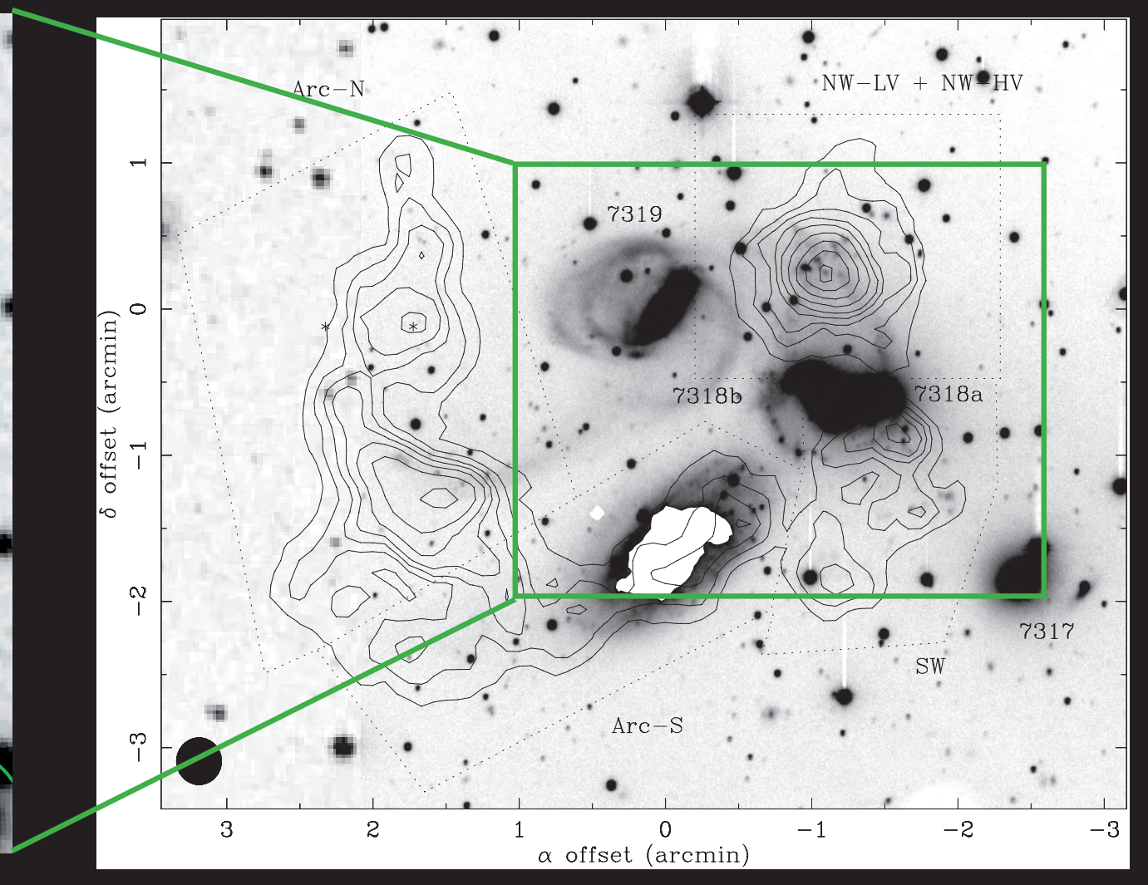
Adaptively smoothed X-ray temperature map with intensity contours, based on the Fe peak method of David et al. (2009). Note that the gas in the shock region is cool.



Exposure corrected 0.3-2.0 keV ACIS-S3 image, smoothed with a 3 pixel Gaussian. Adaptively smoothed contours overlaid.



B_j band image with X-ray intensity contours overlaid. Note that X-ray ridge overlaps spiral arms of NGC 7318b.



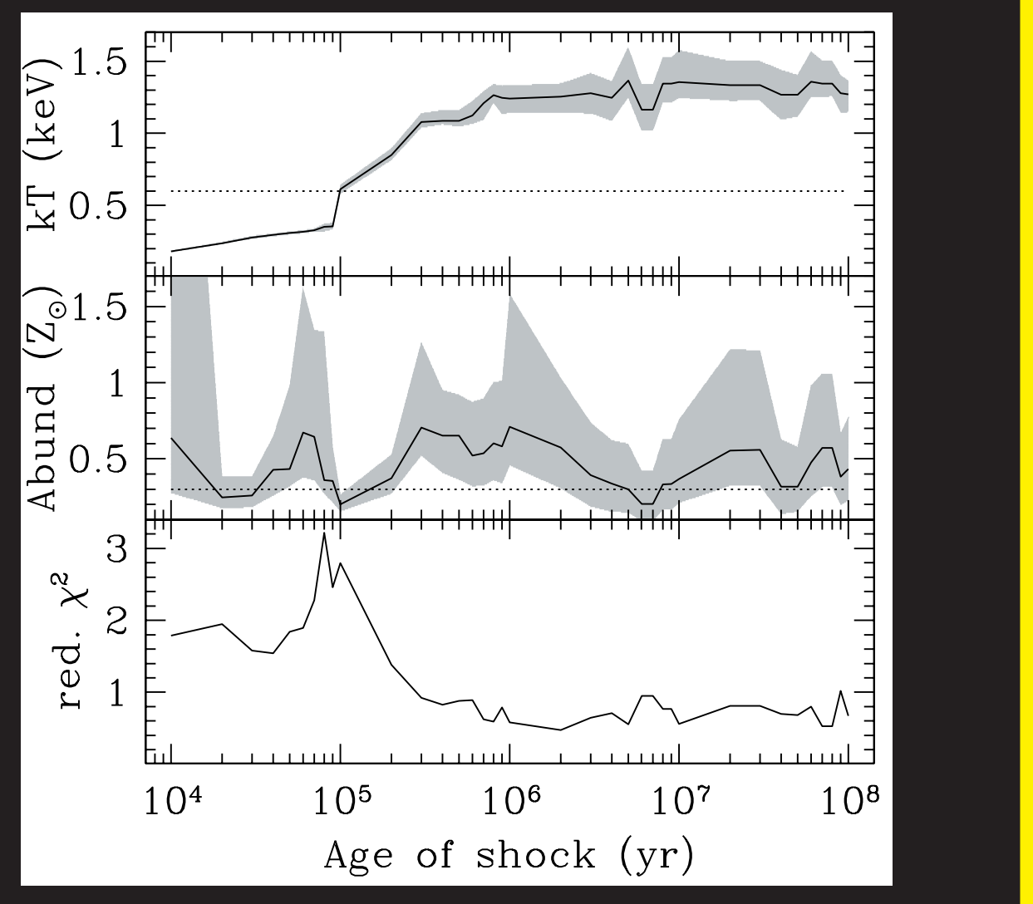
HI map from Williams et al. (2005). The X-ray/radio ridge connects the HI regions, suggesting the collision has shock-heated the cool gas.

X-ray analysis - the shock and

Origin of the IGM: We estimate the total hot IGM mass to be 2.8×10^{10} Msol within ~80 kpc. This is very similar to the HI deficit of the group, $\sim 2 \times 10^{10}$ Msol (Verdes-Montenegro et al. 2001), suggesting that it could be shock-heated HI. However, its extent is large compared to the expected expansion of a shock-heated filament, suggesting that a hot IGM existed in the group before the current interaction.

Temperature of the shock: Spectral fitting shows the ridge to have kT~0.6 keV and 0.3 solar abundance, with a powerlaw component consistent with that expected from High-Mass X-ray Binaries. Spectral mapping (see above) shows the ridge temperature to be similar to its surroundings, and cooler than the large-scale IGM. Based on the velocity of NGC 7318b, we expect the shock to heat HI to 1.2 keV and IGM gas to 1.3-1.5 keV. Possible explanations include:

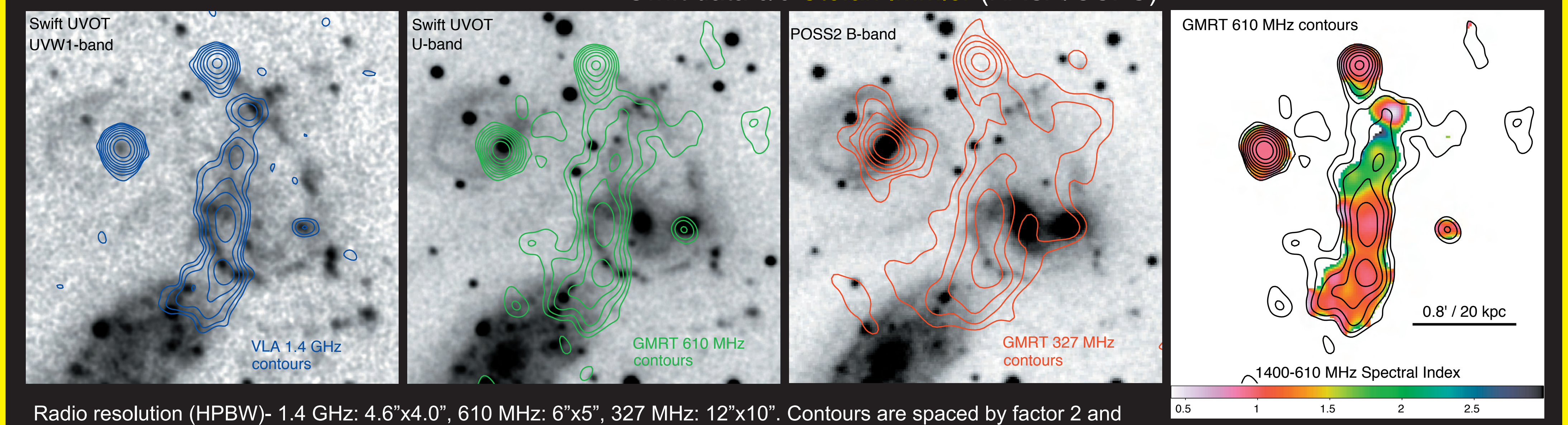
1) Non-equilibrium ionisation plasma in the post-shock gas. Simulations (see right) show that young NEI plasmas would produce low temperatures, but would be very poorly fitted by the APEC model we use.
2) Cooling by collisional heating of dust. Xu et al. (2003) suggest that the post-shock gas could be rapidly cooled by collisions with dust. If so, we would expect the coolest material to be in the ridge, where dust densities should be highest. As this is not the case, dust cooling was probably only briefly effective (Guillard et al. 2009).
3) An oblique shock. A shock with angle ~30° would heat HI or the coolest IGM gas to 0.6 keV, and the angle matches that of the NGC 7318b disk. However we do not see the higher temperatures expected outside the ridge.



Effects of non-equilibrium ionization (NEI) in the shock. Simulated NEI spectra of increasing age were fitted with APEC models to determine whether a young shock might lead us to underestimate the temperature. Results of the fits are plotted above.

Star formation in the ridge

Swift data c/o Stefan Immler (NASA/GSFC)



Radio resolution (HPBW)- 1.4 GHz: 4.6"x4.0", 610 MHz: 6"x5", 327 MHz: 12"x10". Contours are spaced by factor 2 and start at 3σ above the r.m.s. noise level - 0.09 mJy/b for 1.4 GHz, 0.36 mJy/b for 610 MHz and 0.9 mJy/b for 327 MHz.

Morphology: The UV images and radio maps above show that there is considerable star formation in the shock region, which overlaps the spiral arms of NGC 7318b and a northern starbursting region. The radio emission is brightest in the southern part of the ridge, and has a flatter spectral index. A flat spectral index is also seen in the northern star burst. The shock has a steeper spectral index, seen in the northern part of the ridge. These regions are also X-ray bright, showing the influence of star formation on the morphology of the ridge. Low-frequency data shows that the shock emission extends to the east - this is probably older, fading emission, indicating the orientation of the interaction.

Enrichment and cooling: From the UV, the star formation rate in the ridge is estimated to be 1.5 Msol/yr. We estimate the rate of cooling of X-ray gas in the ridge to be 1-4 Msol/yr, sufficient to fuel star formation. We estimate a supernova rate of 4.9×10^{-3} SN/yr, which should enrich the ridge gas to ~0.27 solar abundances, consistent with X-ray measurements.

Conclusions

1) The shock is at a similar temperature to its surroundings, and cooler than the large-scale IGM. It seems likely that the shock was oblique, with and angle ~30°.
2) The mass of the hot IGM matches the HI deficit, suggesting that it was shock-heated in previous galaxy interactions.
3) Star formation has enriched the gas in the ridge to ~0.3 solar, and may be fueled by radiatively cooling gas. Regions of strong star formation contribute to the radio and X-ray flux, but cannot be responsible for the ridge as a whole.

References: David, L.P. et al. 2009, ApJ in press, arXiv:0905.0654 / Eke, V.R. et al. 2004, MNRAS 348, 866 / Guillard, P. et al. 2009, A&A 502, 515 / Mulchaey, J.S. et al. 2003, ApJS 145, 39 / Sulentic, J.W. et al. 2001, AJ 122, 2993 / Trinchieri, G. et al. 2005, A&A 444, 697 / Verdes-Montenegro, L. et al. 2001, A&A 377, 812 / Williams, B.A. et al. 2002, AJ 123, 2417 / Xu, C.K. et al. 2003, ApJ 595, 665