The X-ray View of Centaurus A

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The Many Faces of Centaurus A – Sydney, Australia - 29JUN09

Goals of this Talk

- Present a balanced overview of X-ray observations of Centaurus A made by the current generation of X-ray observatories over the past decade
- Give the non X-ray astronomers a better appreciation of the enormous leap in capability that Chandra, XMM-Newton, and Suzaku represent
- Describe the VLP group's ongoing and possible future work
- Stimulate discussion with attendees at this conference to develop a more complete picture of Cen A – I can't possibly talk about everything in 35-40 minutes!

Outline of Talk

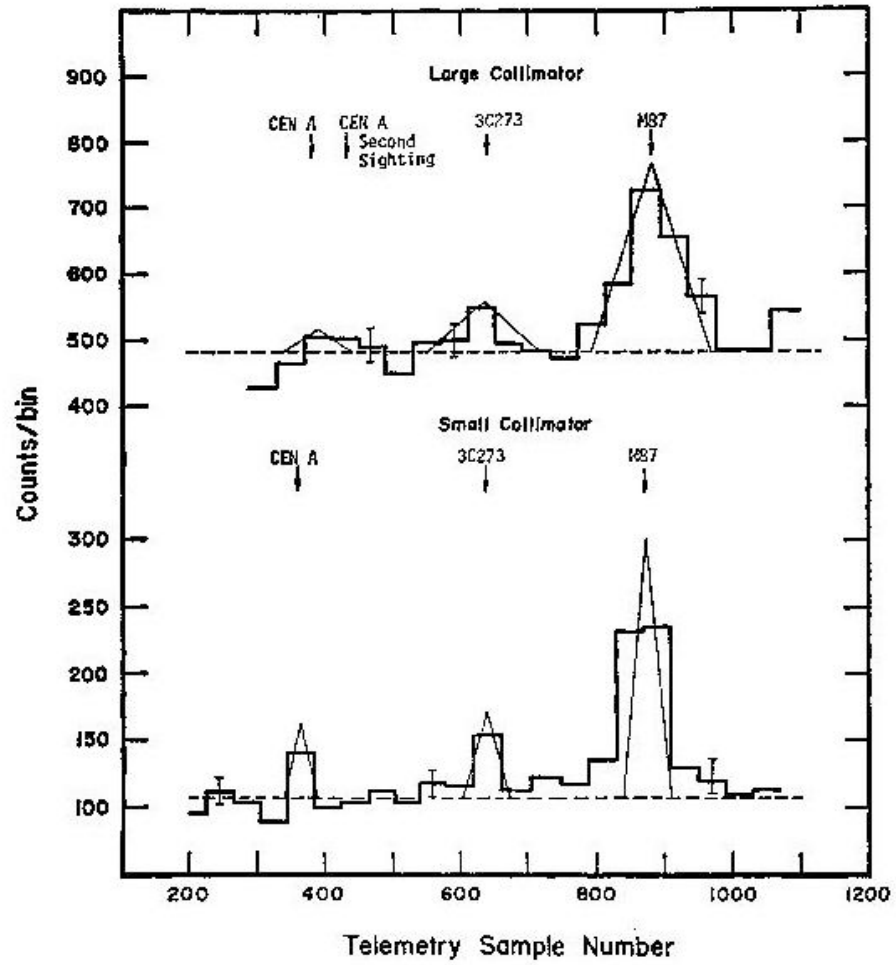
- Introduction/History
- Cen A as an active galaxy
  - Active Nucleus
  - Jet/CounterJet
  - Radio Lobes
  - Large-scale X-ray/radio structure - NML
- Cen A as a 'normal' early-type galaxy
  - LMXB Population
  - Hot ISM
- Future Work/Future Prospects
- Open Questions+Synergies

Cen A in X-rays

Cen A first detected in X-rays by a rocket flight on 14JUN69 (Bowyer et al. 1970)

First imaging observation made with Einstein Observatory (Schreier et al. 1980, Feigelson et al. 1983)

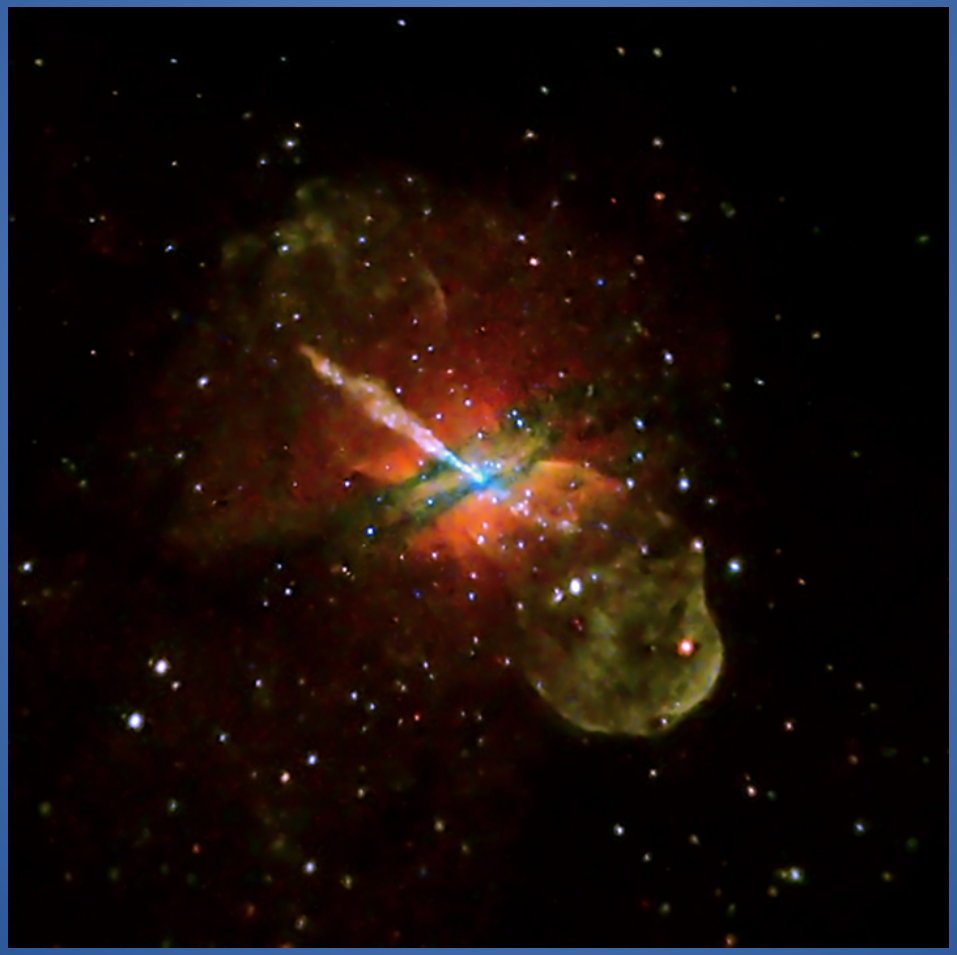
Cen A has been observed with every X-ray observatory



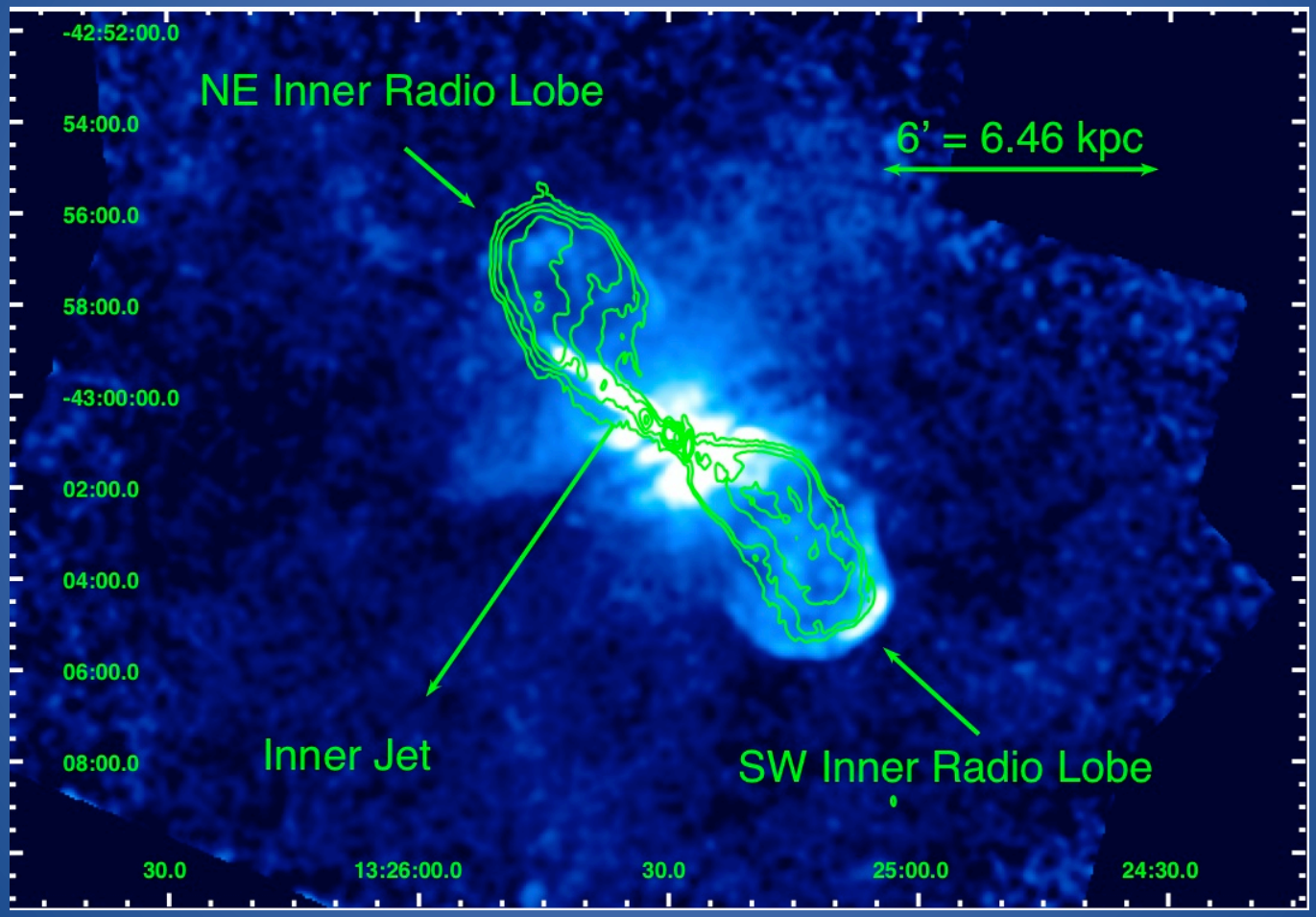
The Current Generation of X-ray Observatories

- Chandra/ACIS – 1000 cm^2 collecting area, sub-arcsecond imaging resolution, moderate ($E/\Delta E=50$) energy resolution
- XMM-Newton/EPIC – 3000+ cm^2 collecting area, 5" imaging resolution (with broad wings), similar ER to Chandra, background is complicated (to say the least)
- Suzaku – 1000 cm^2, 3' imaging resolution, low/clean background, energy resolution below 1 keV is Fano limited
- Chandra HETGS – 25 cm^2, spectral resolution peaks at >1000 at low energies
- Plus Swift, Beppo/SAX etc.

Chandra VLP observation (680 ks) of Cen A – 3 color images created by CXC for press release (red – soft, blue – medium, yellow hard)



Cen A VLP – X-ray/Radio Overlay with point sources removed

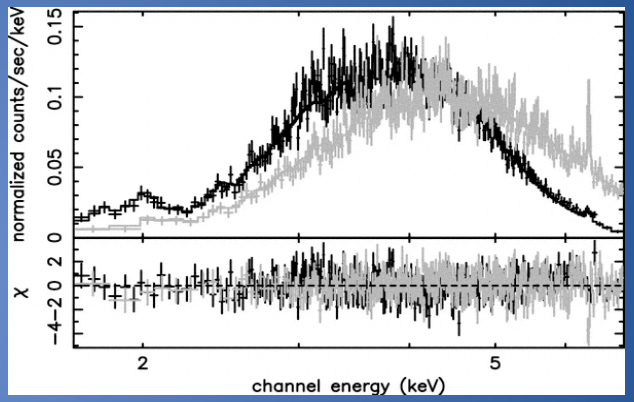


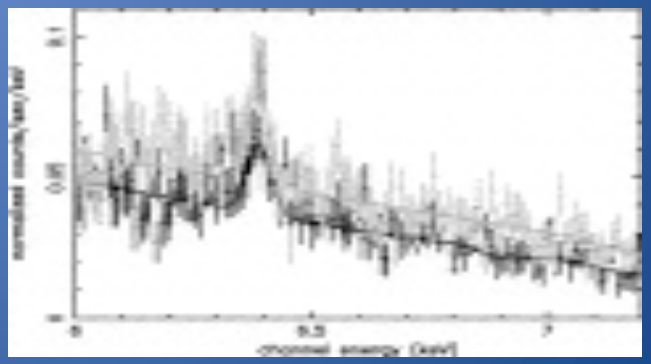
The Active Nucleus

HETGS/XMM/Suzaku spectra of active nucleus

- $M_{SMBH}=1.1\times10^{8}\ M_{solar}$ (Marconi et al. 2006)
- $L_x=5\times10^{41}$ ergs s^{-1}
- Spectrum well fit by two heavily absorbed power-law models
- HETG observations – fluoresence from cold Si, S, and Fe
- Width of Fe line <20 eV (50 km s^{-1}) (Evans et al. 2004)
- Markowitz et al. (2007) also report cold lines of Fe, Si, S, Ar, Ca, and Ni
- They find [Fe/H]=+0.1 (in absorption) – circumnuclear material enriched

HETG spectrum of Cen A nucleus





Chandra sub-arcsecond imaging of Nucleus

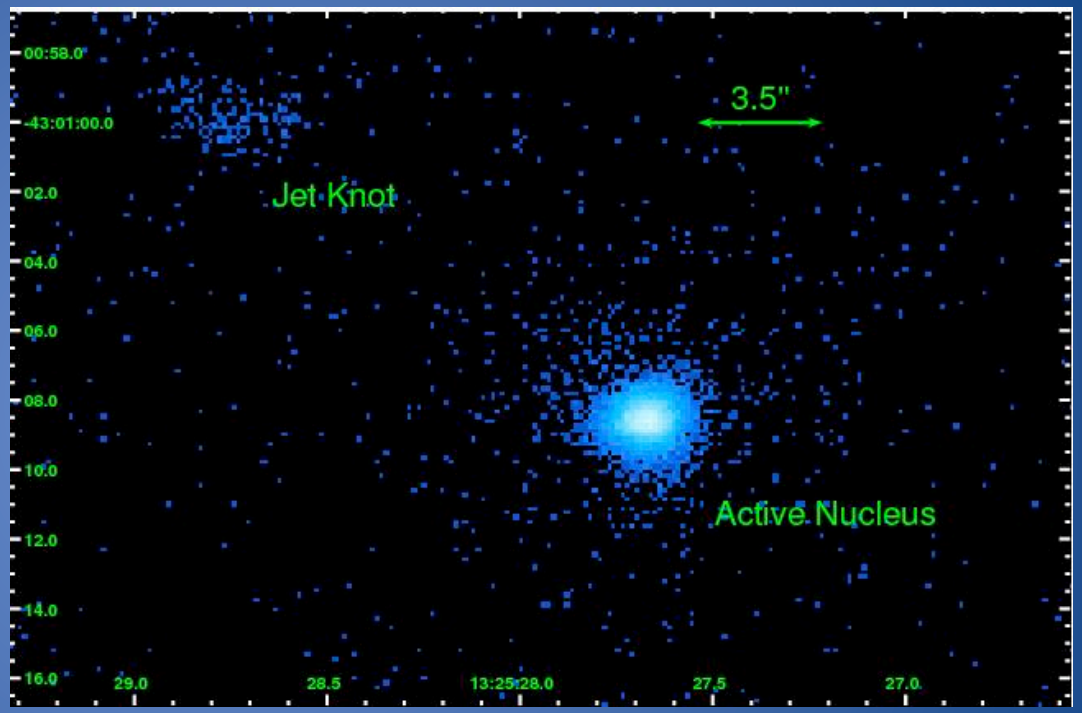
Is the nucleus of Cen A resolved by Chandra?

Answer: Maybe!

HRC observations of nucleus in this AO (PI: M. Karovska) to resolve this issue

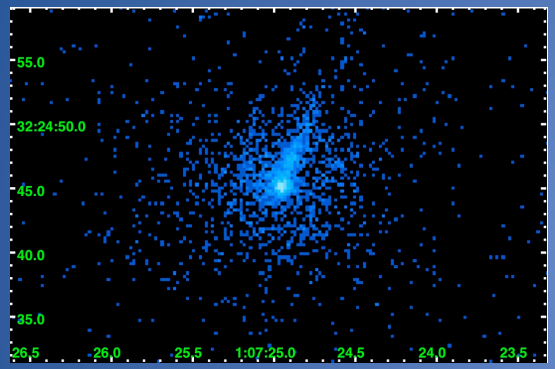
Could we be seeing the torus (probably not)? Jet structures? RPK interpretation – dust scattering halo (?!?)

Chandra HRC observations of Cen A nucleus



X-ray Emission from FR I Jets - Synchrotron

3C 31



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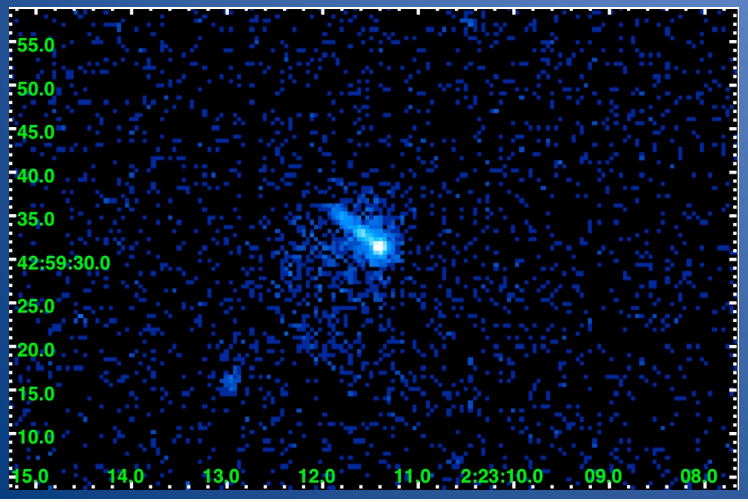
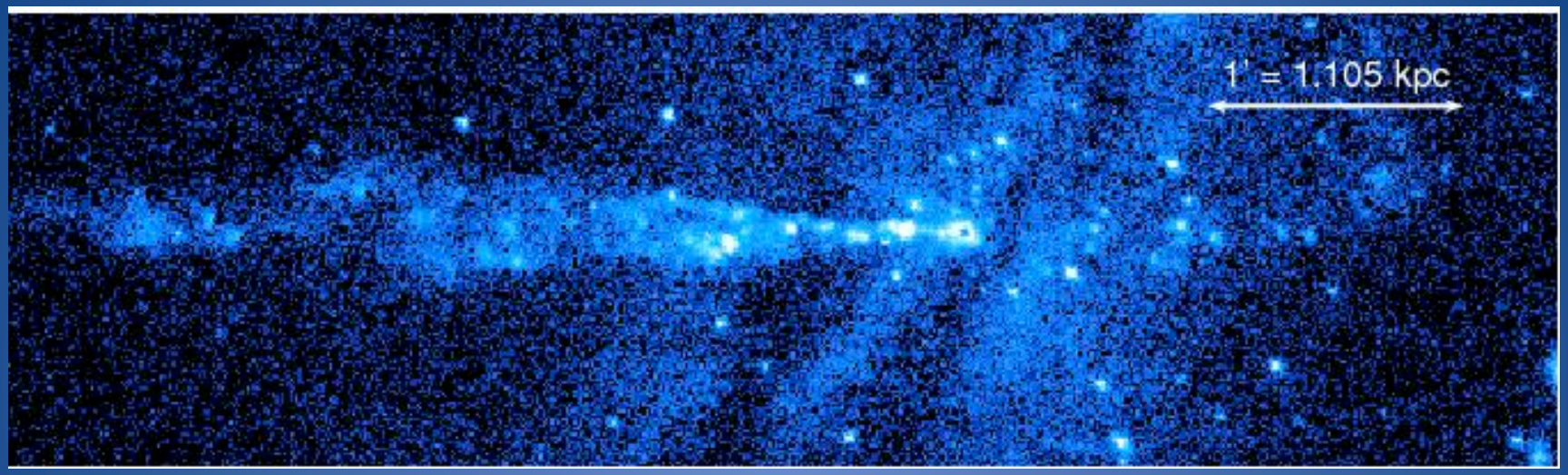
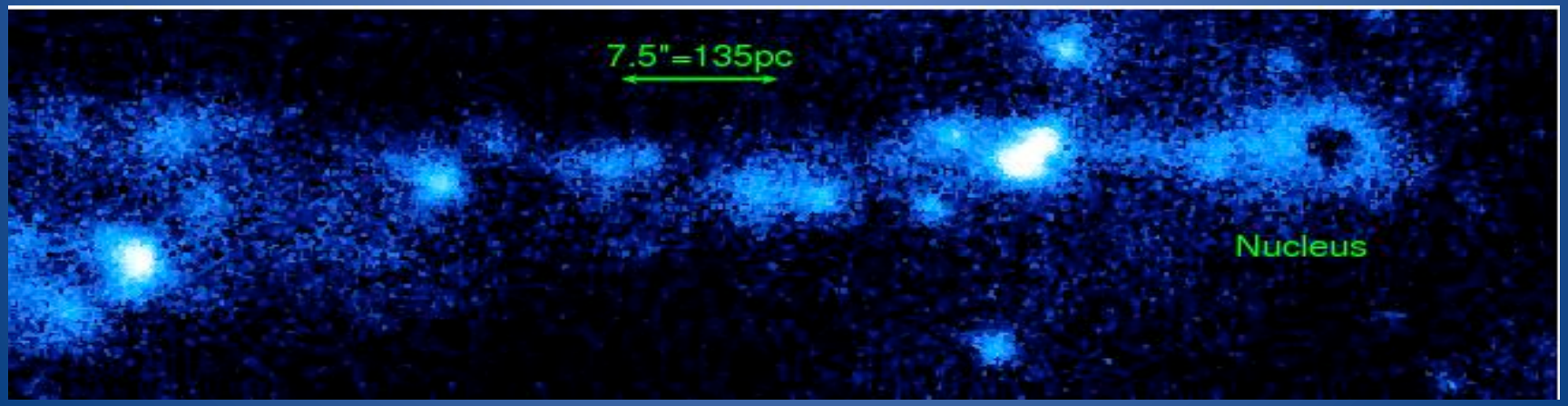


X-ray emission from FR I jets – generally believed to be synchrotron radiation from ultrarelativistic ($\gamma=10^7$-10^8) electrons created in shocks in the flow

Particle lifetime is 10-100 yrs in typical equipartition fields – because of its proximity, Cen A is the only radio galaxy in which Chandra probes the scales of particle acceleration and radiative loss

Cen A Jet – X-ray Overview





X-ray/Radio Comparison of Inner Jet Region

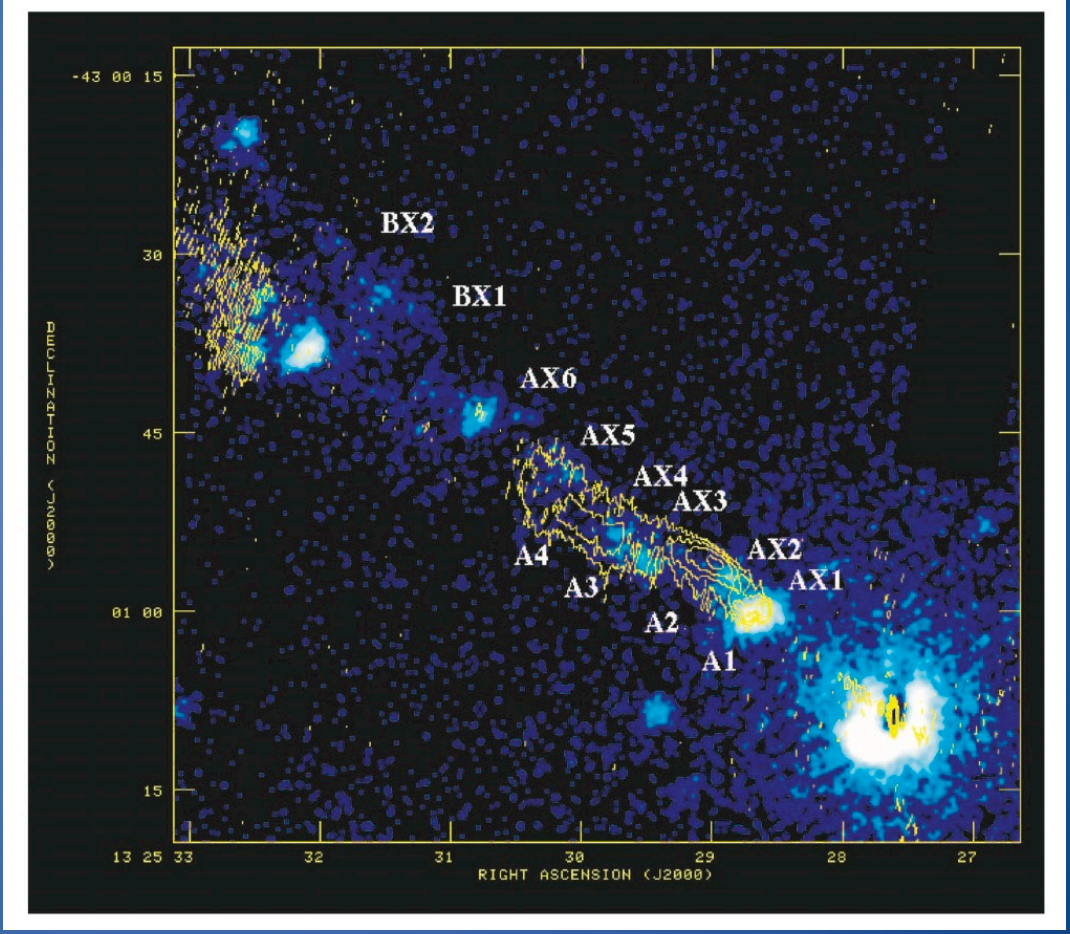
Cen A Jet

The X-ray morphology of the Cen A jet is obviously far more complicated than a few shocks in the flow

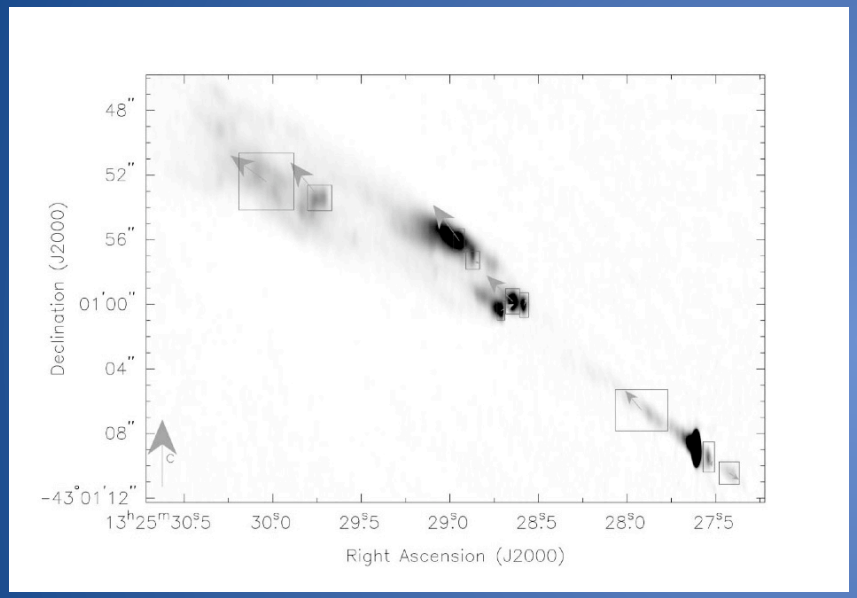
There are 49 knots in the jet all of which are spatially extended – (Kraft et al. 2002, Hardcastle et al. 2003, Kataoka et al. 2006, Goodger et al. in preparation). Several unresolved sources are probably foreground/ background LMXBs unrelated to the jet

Discrete knots are embedded in continuous diffuse emission – VLP observation shows that this is truly diffuse (Hardcastle et al. 2008)

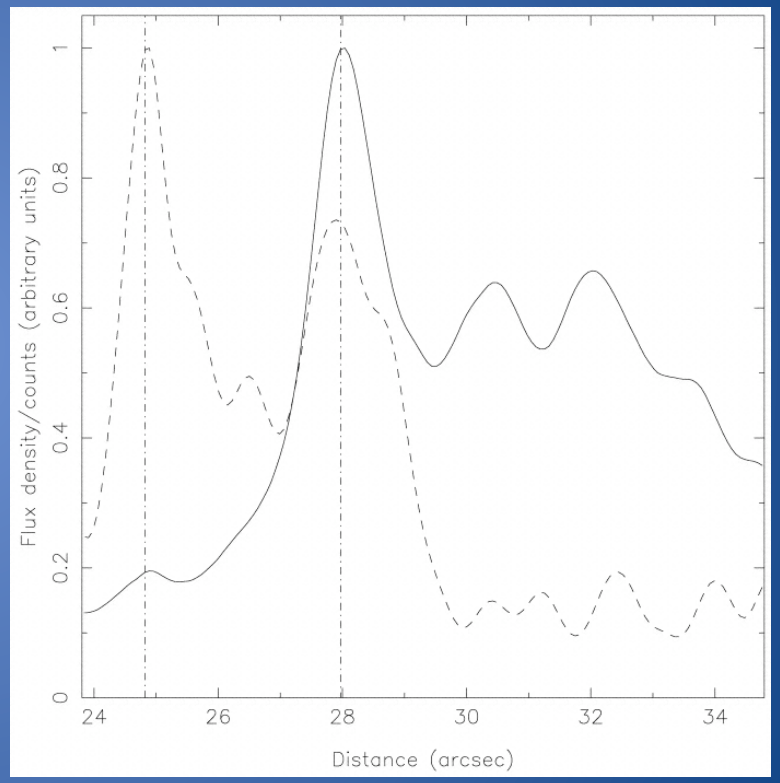
Spectrum of knots is well fitted by single absorbed power-law models with photon index between 2.0 and 2.4 – supports synchrotron interpretation



X-ray/Radio Knot Offsets and Radio Knot Proper Motion (Hardcastle et al. 2003)



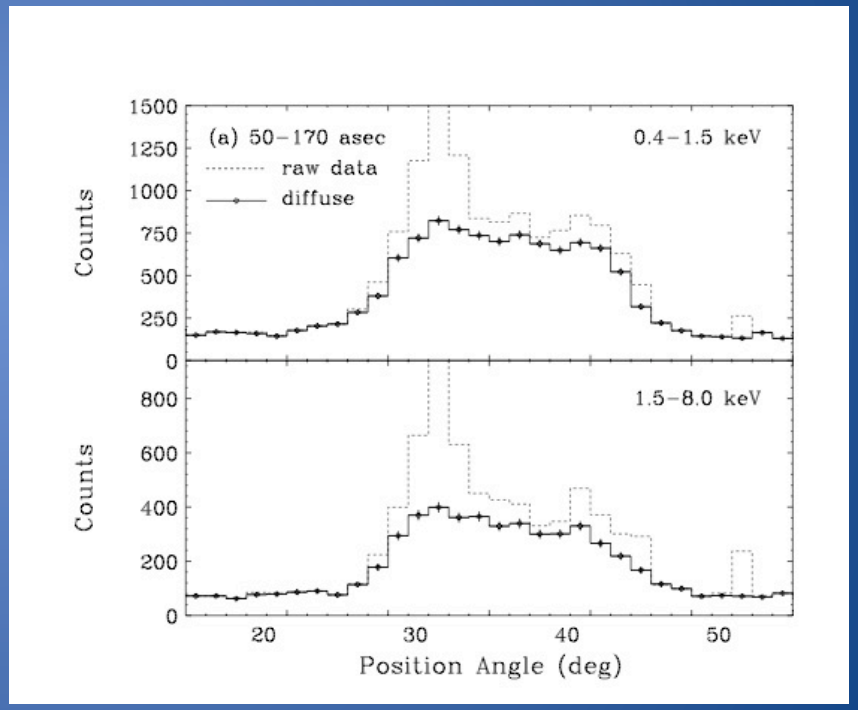
Knots with highest X-ray/radio flux densities not moving
Suggests the bright X-ray knots are the result of interactions with an impediment in galaxy



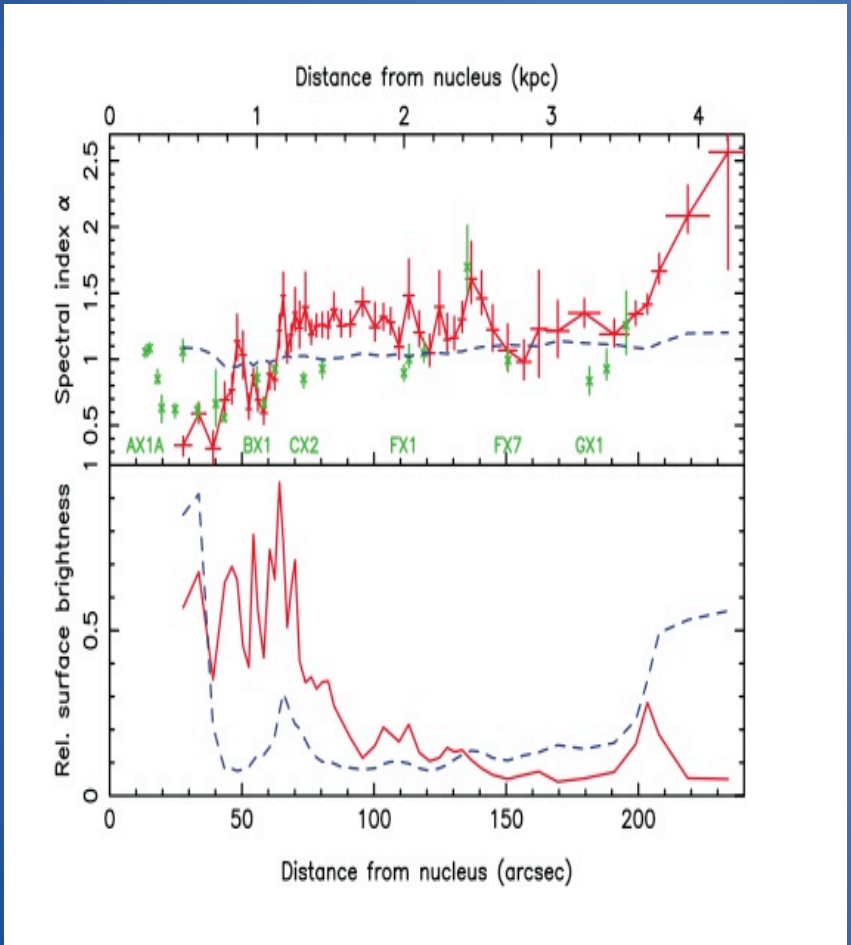
Solid line – radio profile, dashed line – X-ray profile around knots A3/4

Is there a difference between 'knots' and diffuse emission (Kataoka et al. 2006)?

- LF of jet knots suggested unresolved emission is truly diffuse
- Diffuse emission (after removal of 'knots') is flat topped and edge brightened
- Edge emission may have flatter spectrum
- Suggests velocity shear in jet



Spectral Index variations along jet (Hardcastle et al. 2008)



Top figure – X-ray spectral Index of diffuse features in red, X-ray spectral index of knots shown in green, and radio/X-ray spectral index shown as blue

Bottom figure – Radio (dashed) and X-ray (solid) intensities (arbitrary units)

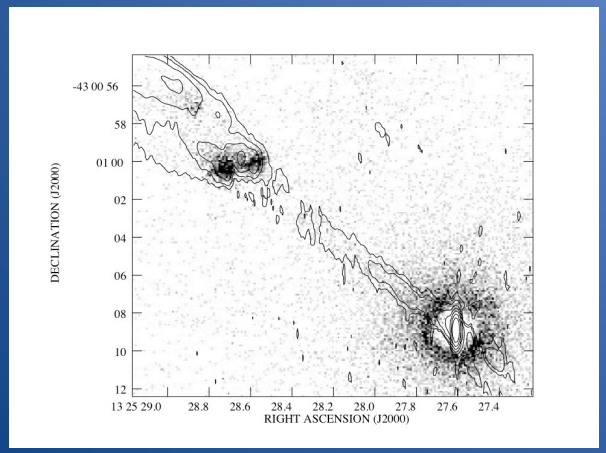
3 regions defined – central 1' dominated by knots, 1'-3' with both knot and diffuse features, >3' steep spectra of lower efficiency

X-ray and Radio Knots (M. Hardcastle, et al. 2003, J. Goodger, Ph.D. Thesis – University of Hertfordshire)

Types of knots

Project to characterize X-ray spectral, X-ray/radio, proper motion, and polarization properties of jet knots

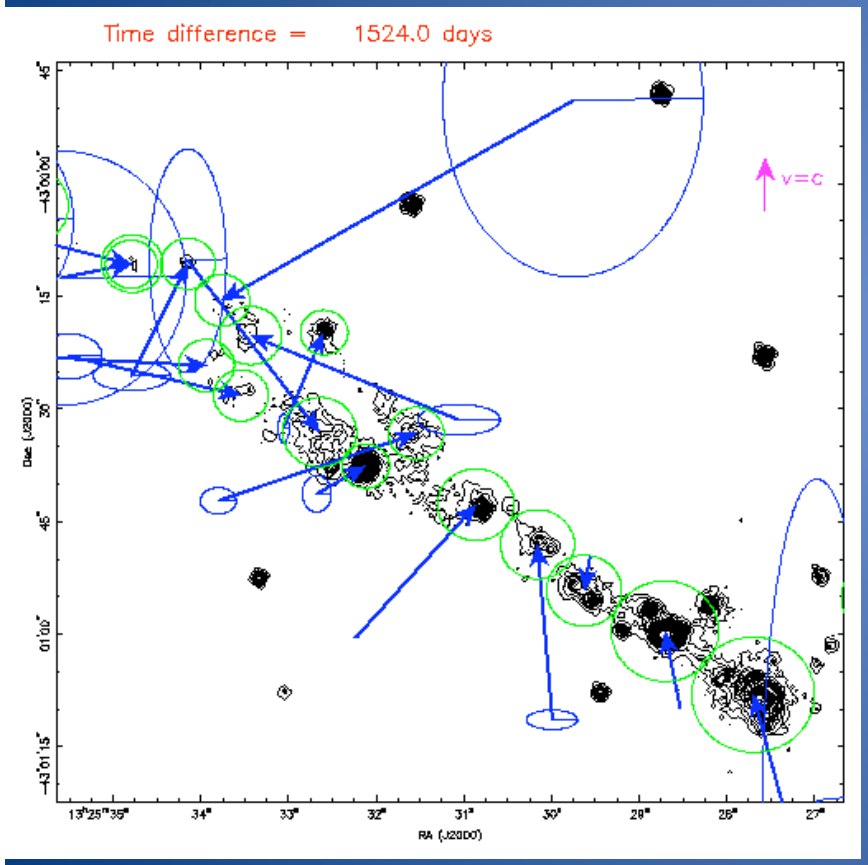
Knot Type	Number
X-ray and Radio	13
X-ray Only	27
Radio Only	9



Conclusions of work

- X-ray only knots have flatter spectra than X-ray/radio knots and may represent a different population
- No impulsive particle acceleration in any X-ray knot (unlike HST-1 in M87)
- X-ray/radio knots are probably result of collision with stationary object
- Knot A1 is a recollimation shock

Proper Motions of X-ray Knots (M. Birkinshaw, in preparation)



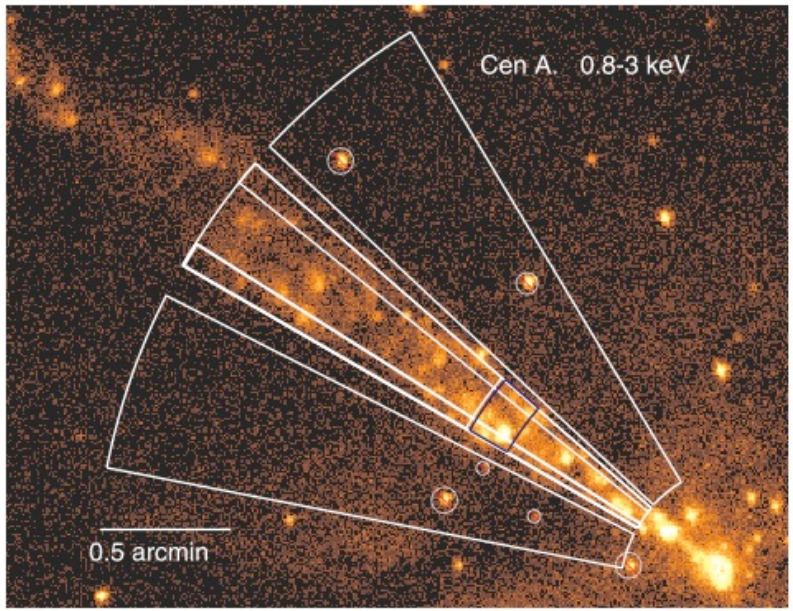
Cross-correlation of X-ray images

Green circles define regions cross-correlated, blue arrows the best-fit shift vector between epochs, blue ellipses show errors

No significant detection of proper motions, results limited by counting statistics in AO1 datasets

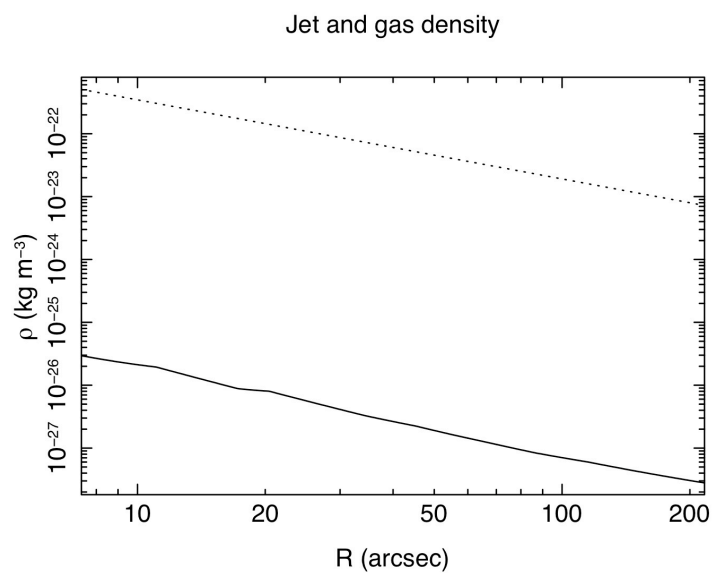
Clues to Underlying Jet Dynamics

Spectral Structure of X-ray Knots (D. Worrall et al. 2008)



Spectrum steepens with increasing distance from jet axis due to change in spectra of knotty emission – contrary to spine/sheath model, suggests possible knot migration

Hydro model of jet dynamics (P. Nulsen, D. Stark, et al. in preparation)



Chandra resolves external gas and width of jet – 1D hydro model using inputs of P_{jet}, p_{ism}, and v_{jet} can explain NE/SW lobe asymmetries

Big Picture – What does it all mean?

- The complex structures we observe in the Cen A jet defy understanding in terms of simple models
- There may well be several different particle acceleration processes occurring in the jet
- Shear flow versus stationary shocks? Jury still out
- Without Cen A, we wouldn't be talking about these phenomena
- The way forward is continued observations – additional theoretical work necessary too!

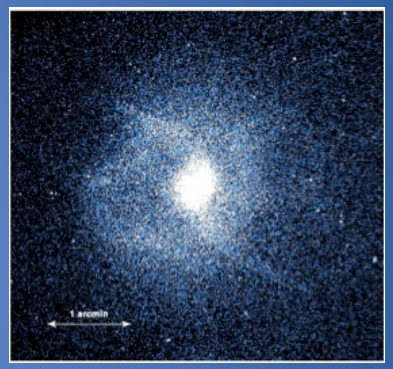
Supersonic Inflation of Radio Lobes

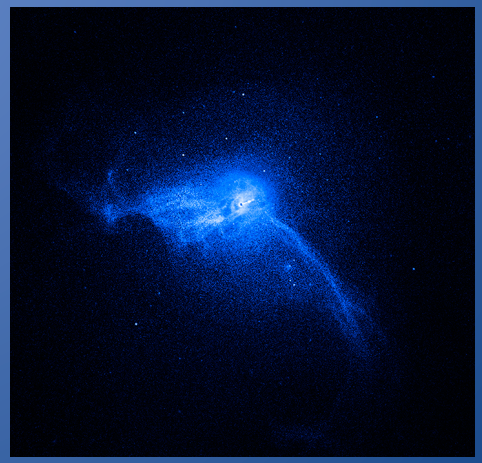
Chandra has seen the shocks, filaments, and other features in the gas indicative of feedback between the gas and the central SMBH

For massive systems (i.e. clusters) – regular outbursts can resolve the cooling flow problem

For less massive systems (i.e. groups) – nuclear outbursts can explain entropy floor and unbind a large fraction of the gas

NGC 4636 (top) and M87 (bottom)



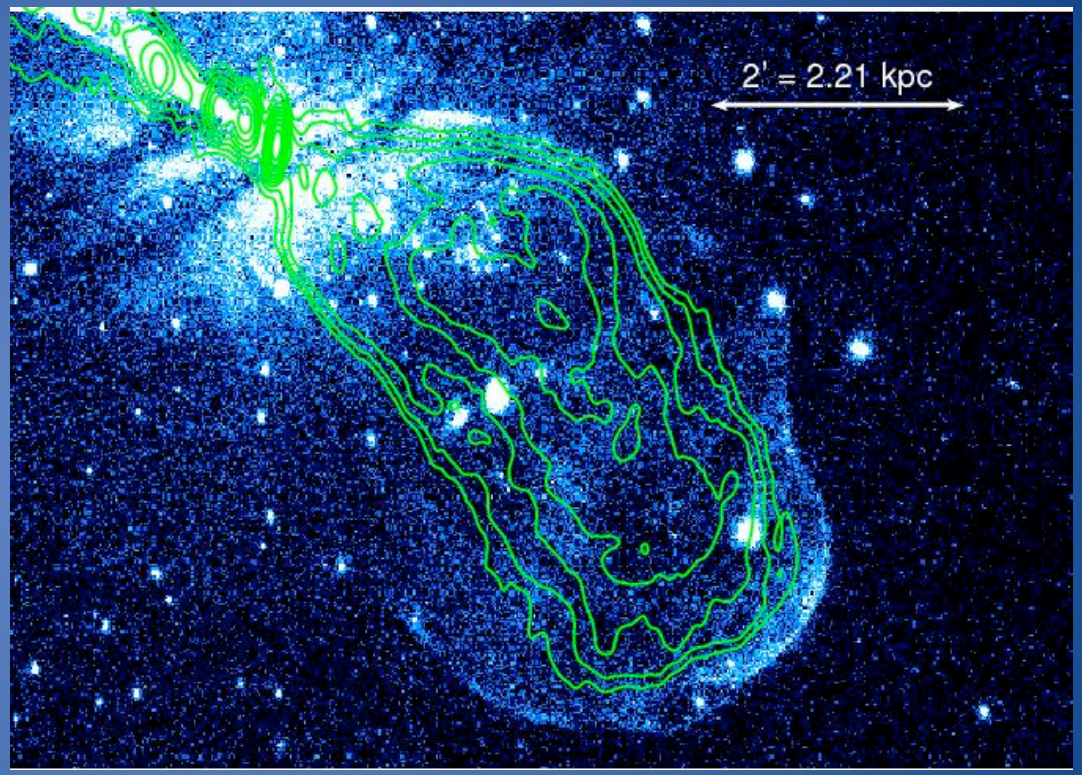


X-ray emission from SW radio lobe (Croston et al. 2009 and this conference)

X-ray shell of emission around SW radio lobe - initially attributed to thermal shell (Kraft et al. 2003)

Most of the emission around the SW half of the lobe is synchrotron emission around NE half is thermal

$P_{lobe}=6x10^{42}$ ergs s^{-1}
$V_{lobe}=2500$ km s^{-1}
$\tau_{lobe}=3x10^{6}$ yrs

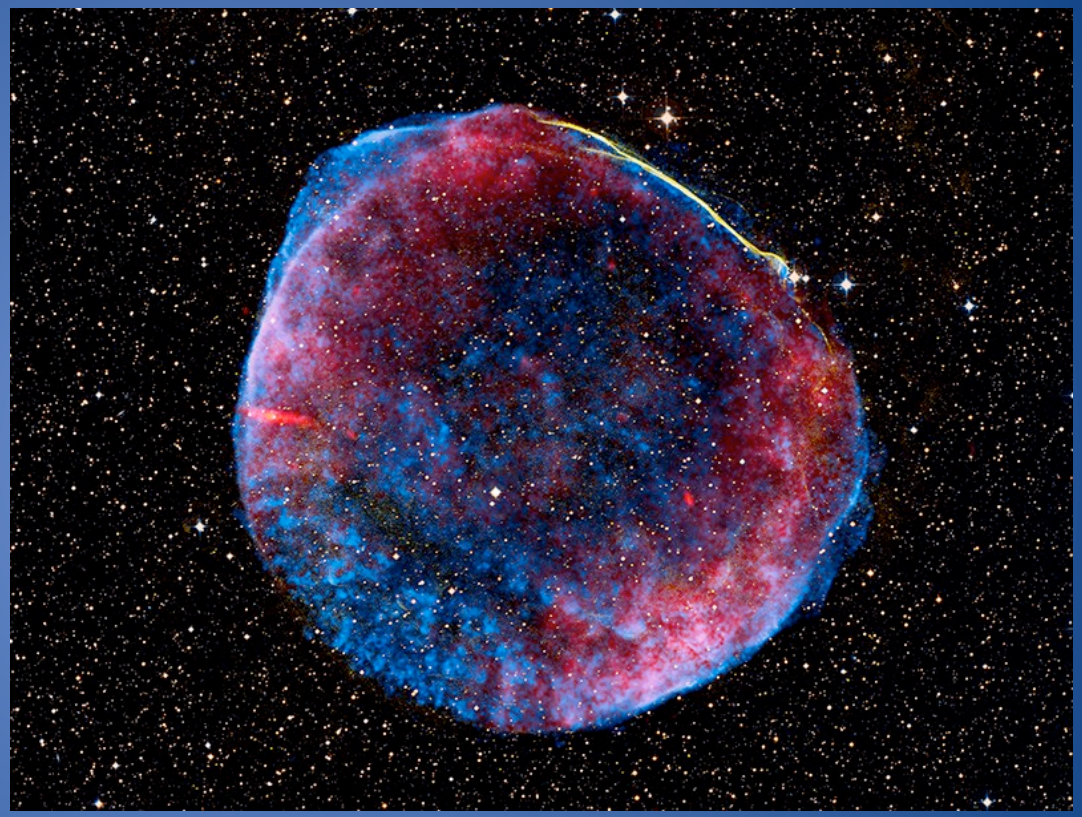


Implications

Particle acceleration in RG shocks similar to that observed in Galactic and Magellanic SNRs

There could therefore be a large difference between T_e and T_p behind the shock (Kraft et al. 2007).

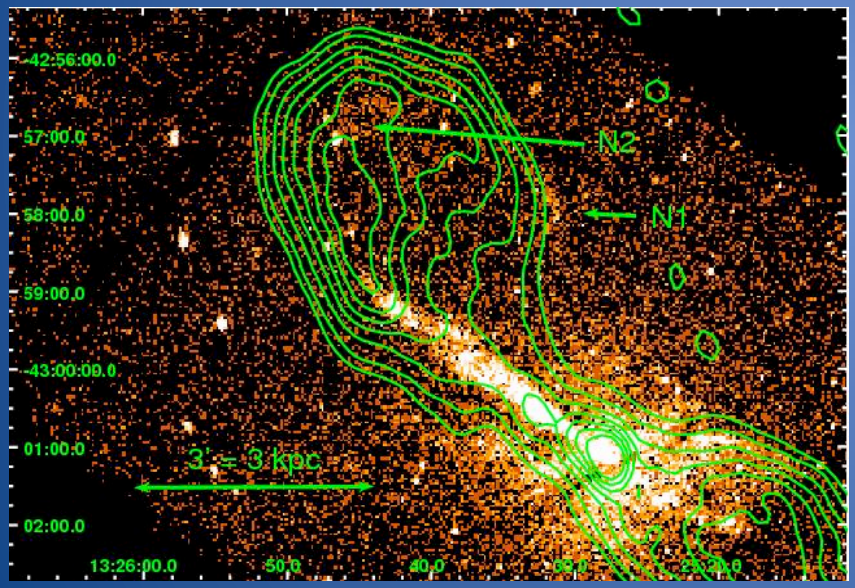
Energy in shock equal to thermal energy of all (hot) gas within 10 kpc



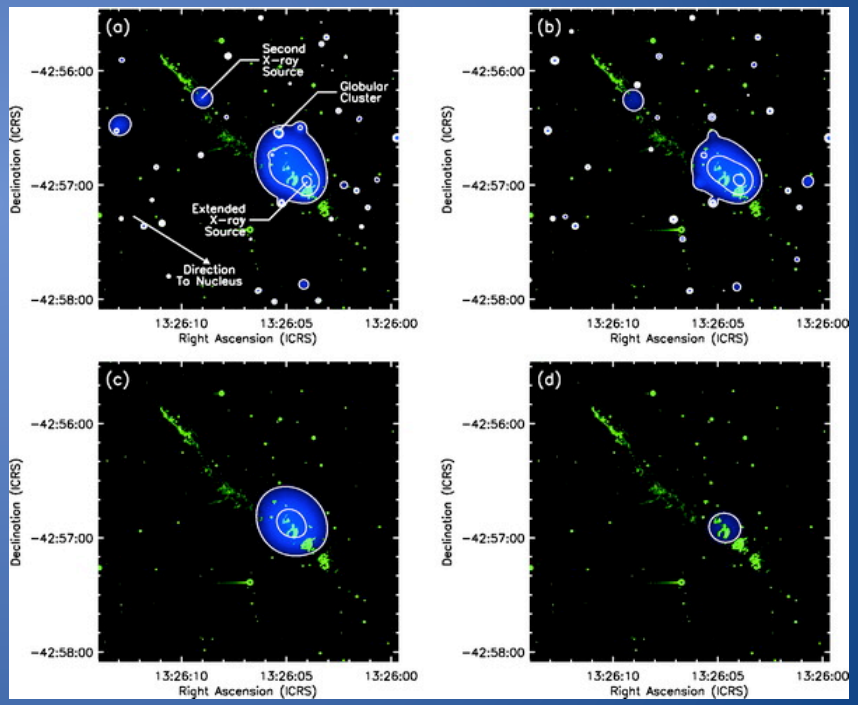
SN1006 (taken from APOD): blue is X-ray (Chandra), red is radio, and yellow optical

Northeast Inner Lobe and Large scale jet

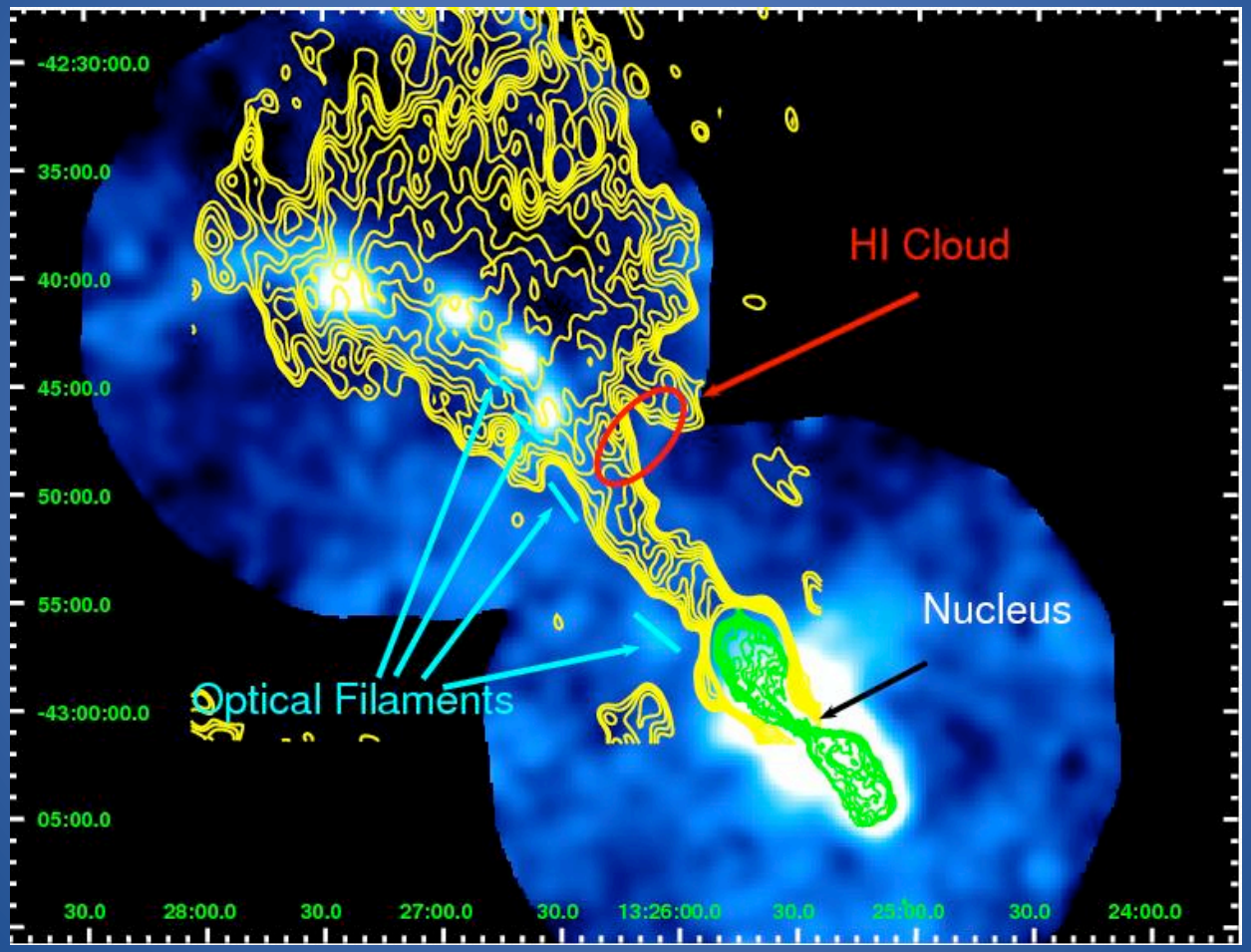
NE Inner lobe (Kraft et al. 2007) – emission likely thermal (shocks?)



X-ray emission from optical filaments (Evans and Koratkar 2004)

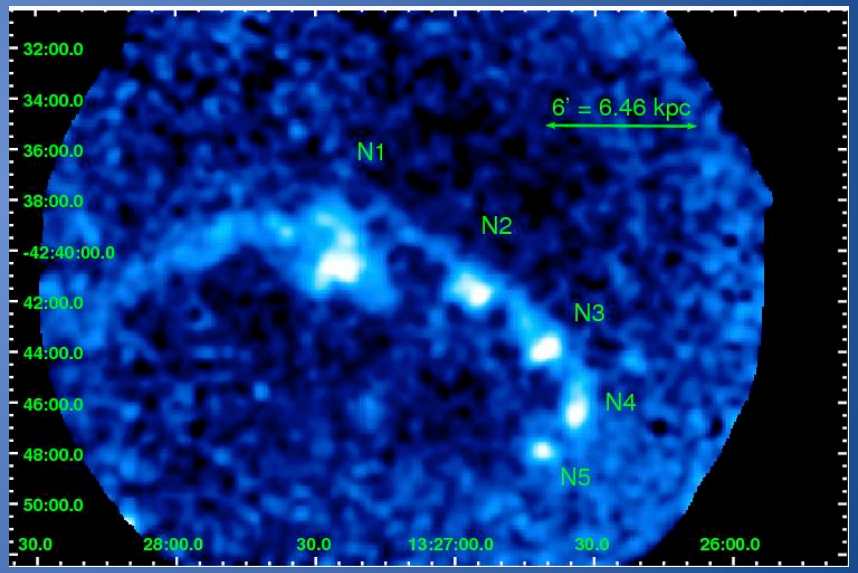


XMM-Newton Image of Cen A with radio overlays (XMM M1+2 0.3-1.0 keV)



NML X-ray Filament (M1+2 – 0.5-2.0 keV)

- X-ray filament consists of 5 resolved knots connected by diffuse 'thread'
- Emission is thermal in all cases (strong Fe L bump)
- $P_{knot} > P_{ISM}$ ($P_{eq} = P_{ISM}$)



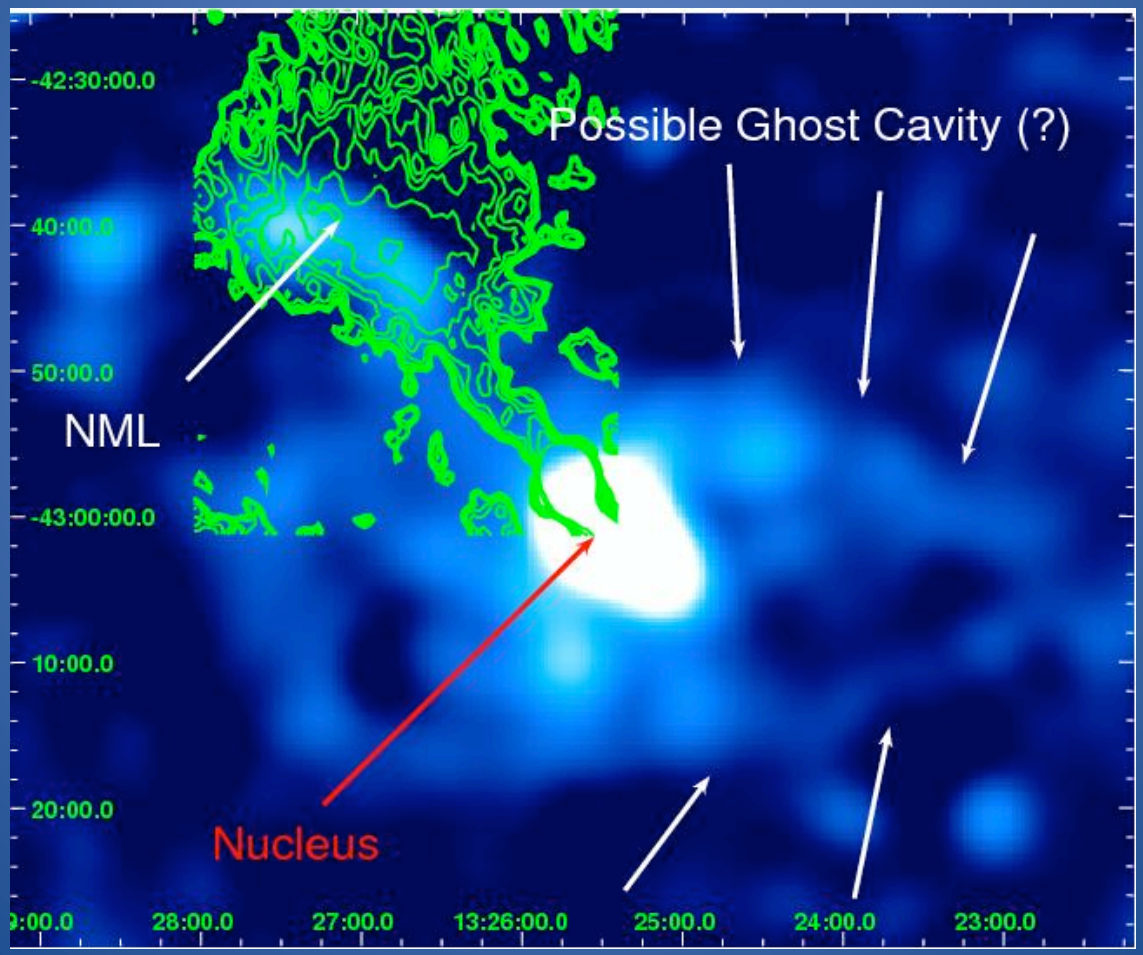
Origin of X-ray Filament

- Age of NML 100-200 Myrs (Saxton et al. 2003)
- Age of SW inner lobe 3 Myrs
- Overpressurization means filaments are YOUNG (i.e. related to current outburst – not the one that created the NML)
- Photoionization by beamed flux from nucleus – NO
- Starburst/superbubble – NO
- Jet heating cold gas? Only viable option in our view (Kraft et al. 2009)

Cold gas filament in Cen A?

- Young blue star stream from a disrupted dwarf galaxy (Peng et al 2004 – figure at right)
- Some dwarf galaxies in Cen A group have been ram pressure stripped of gas (Bouchard et al. 2006)
- Could the filament of hot gas in Cen A be the result of stripped gas from a dwarf galaxy?

ROSAT PSPC image (14 ks!?!?!?!) – Possible ghost cavity to Southern Middle Radio Lobe



Cen A as a radio galaxy – final thoughts

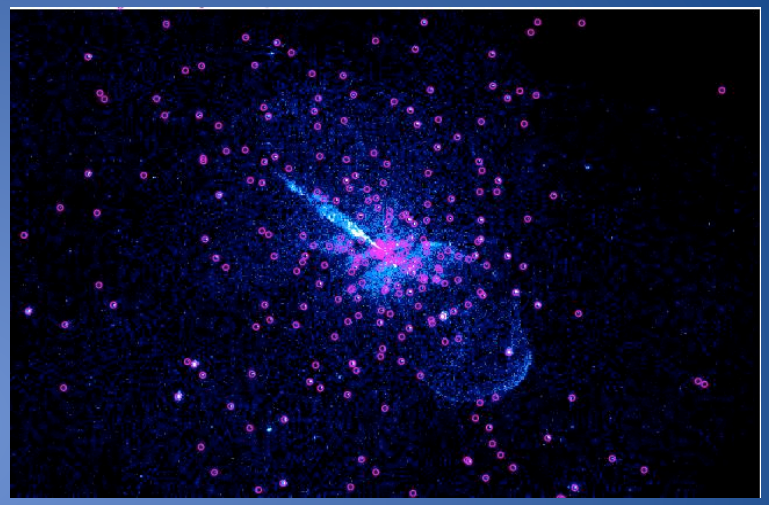
- KEY RESULTS
  - Large number of X-ray knots (currently 49) plus diffuse synchrotron emission distributed throughout the jet
  - Proper motions of radio knots
  - X-ray/radio features appear to be stationary
  - NE jet kinetically dominated/SW lobe thermally dominated
  - SW lobe inflating highly supersonically
  - Thermal gas filament associated with NML – NML still being (re?)powered

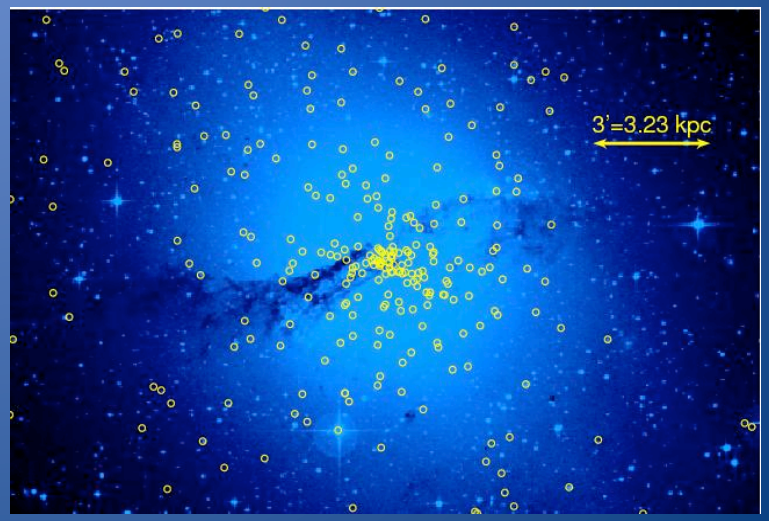
Cen A as an early-type galaxy

- Cen A is the nearest massive early-type galaxy (M_B=-20.28) and the nearest late stage merger
- X-ray observations reveal a rich population of LMXBs (Sco X-1 like – NS primary and K/M dwarf secondary) and other compact binaries
- X-ray emitting gas (0.5 keV) with complex morphology due to merger and nuclear outburst

X-ray Binaries in Early-Type Galaxies

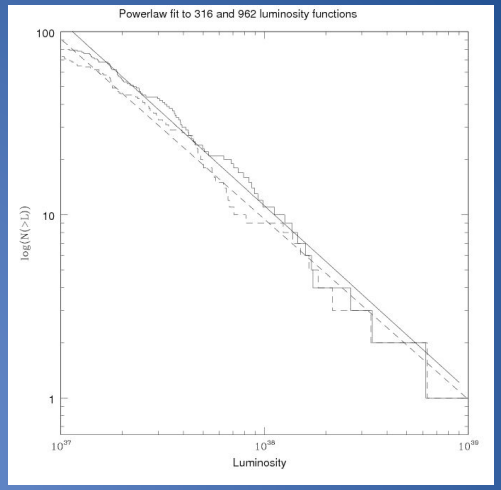
- Previous generation of X-ray observatories (ROSAT and ASCA) inferred presence of LMXBs based on spectra
- Early Chandra observations confirmed large numbers of LMXBs (hundreds per galaxy) in ellipticals with $L_x > 10^{37}$ ergs s^{-1}
- AO-1 Chandra observations: 246 point sources $L_x > 2 \times 10^{36}$ ergs s^{-1} (Kraft et al. 2000, Kraft et al. 2001)

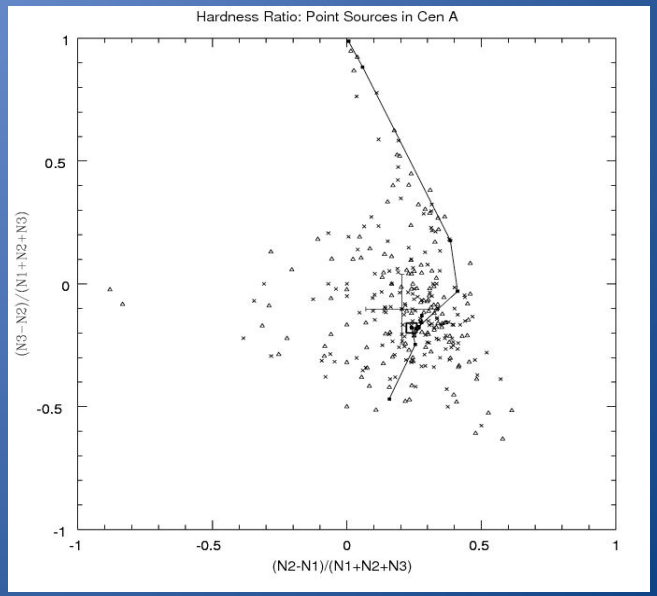




Early Results on Point Sources

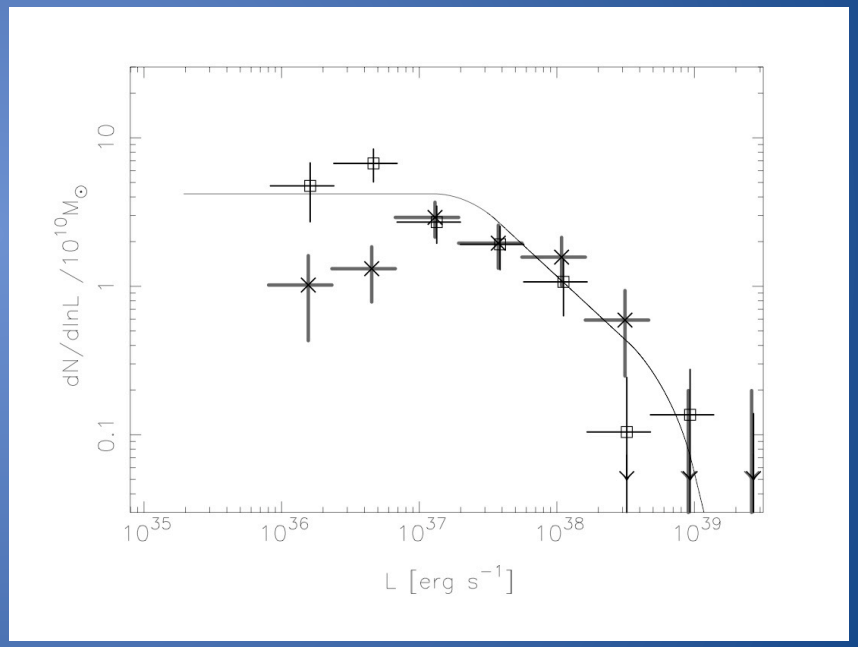
- Color-color diagram and luminosity function shown to the right
- No sources are extended at the resolution of Chandra (i.e. no obvious SNRs)
- Several heavily absorbed, flat spectrum sources in dust lane (HMXBs?)
- Color-color diagram and source distribution may give important clues about various types of sources
- 2 ULXs in Cen A (Ghosh et al. 2005, Sivakoff et al. 2008)





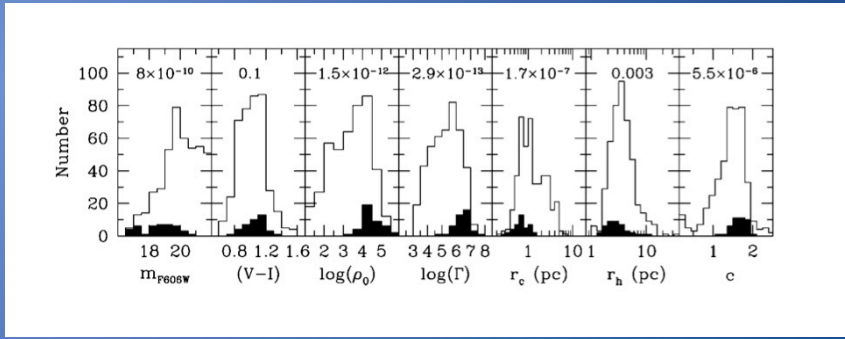
The GC/LMXB Connection – Are all LMXBs formed in GCs?

- Typically 30-50% of LMXBs coincident with GCs
- 30% for Cen A (Minitti et al. 2004, Rejkuba et al. 2004, Woodley et al. 2008)
- Woodley et al. (2008) found that LMXBs are more likely to be in red GCs than blue GCs
- Could all LMXBs be formed in GCs? NO!
- Voss et al. (2009) claim differences in LF for GC sources versus non-GC sources below 10^{37} ergs s^{-1}

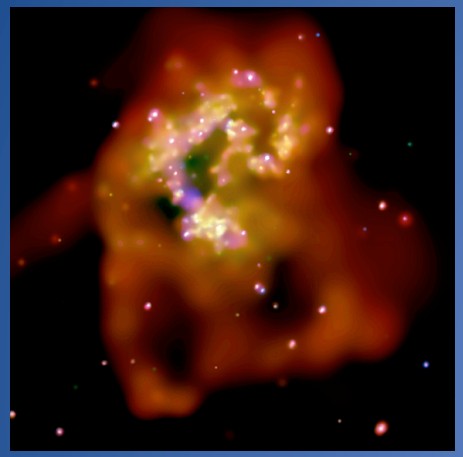


Point Sources – the Chandra VLP

- 650+ total point sources
- LMXBs found in the densest GCs with compact cores (Jordan et al. 2008)
  - Complete source list
  - Characterize spectra
  - Variability
  - Optical IDs!
- VLP – $L_X=10^{37}$ ergs s^{-1}=300 counts (150 sources), several dozen with more than 1000 counts



Chandra Observations of Merging Galaxies



Chandra has observed a large number of merging galaxies – Cen A is the nearest massive (late-stage) merger

The Antennae (show at left – X-ray/top HST/ bottom) is perhaps the best example due to its proximity and X-ray luminosity (Fabbiano et al 2001, Baldi et al. 2006, among many others)

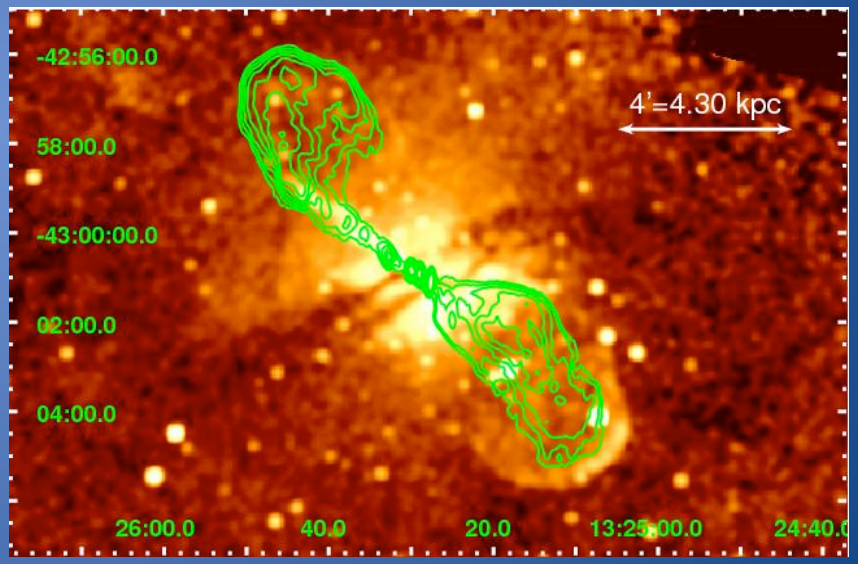
Brassington (Ph.D. thesis – University of Birmingham) found a complex relationship between the X-ray luminosity and age of merging galaxies by using Chandra to study a sample over a range of merging states

Hot ISM – central few kpc

Morphology and temperature

- Gas is far from hydrostatic equilibrium
- Multiple surface brightness discontinuities, complex spatially variable absorption
- Note NE/SW asymmetry in gas structure
- Temperature structure around spiral component COMPLEX! – Fit 13 different regions – often a 2-3 component model (1-2 APEC + PL) with variable absorption doesn't describe data

0.5-1.0 keV Chandra VLP image with radio contours overlaid

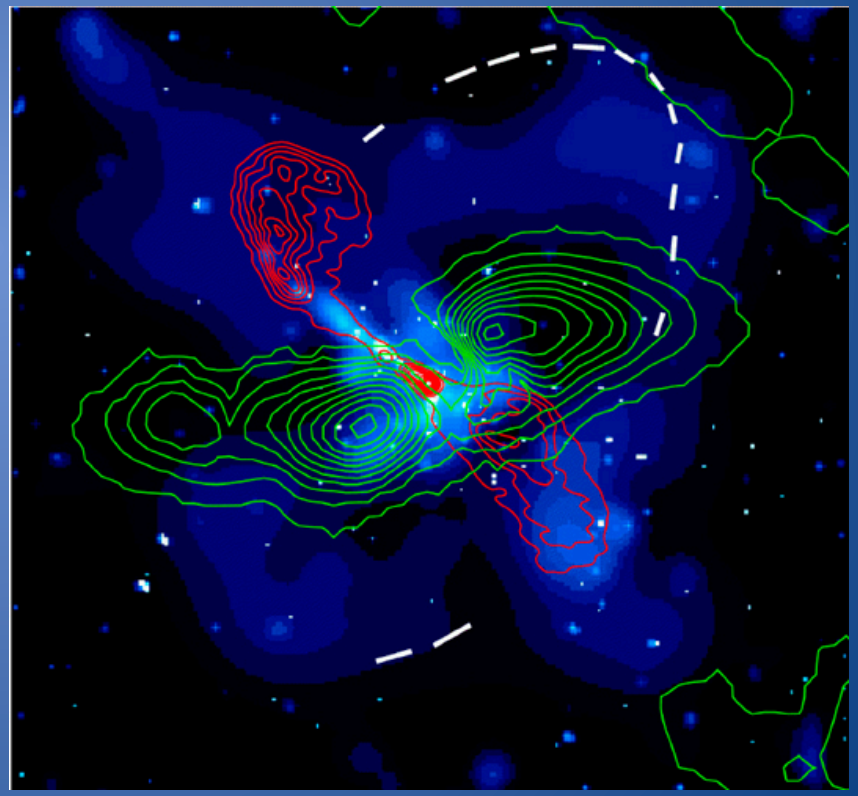


Cen A Arcs (Karovska et al. 2002)

Complex structure of hot ISM

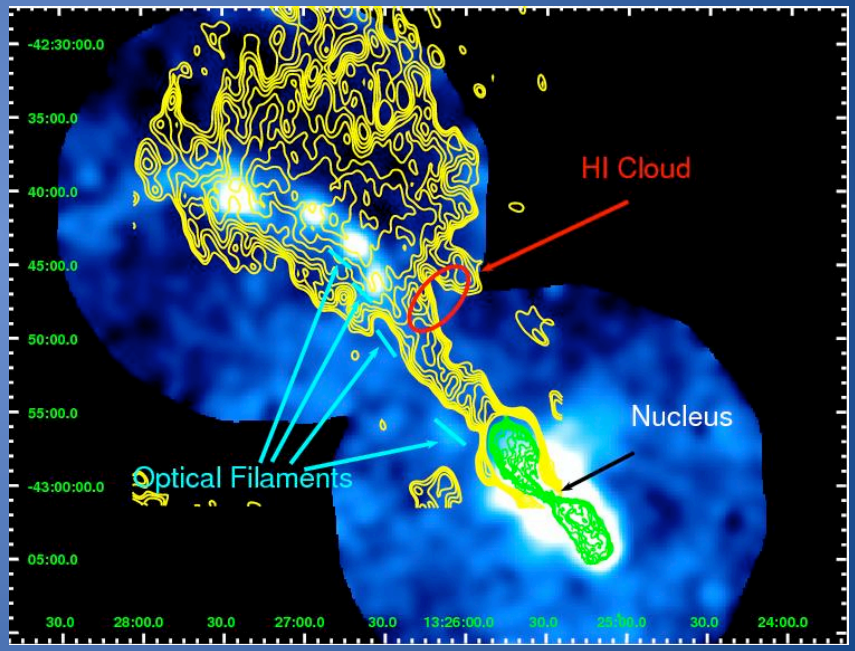
- Adaptively smoothed Chandra HRC image
- X-ray Cavities more or less coincident with HI peaks
- Arcs of gas extending 8 kpc or so from nucleus.

Blue – Chandra HRC, red-radio continuum, green-HI



Large scale gas structure

- Extended gaseous corona – too large to observe easily with Chandra/ XMM-Newton/Suzaku
- n_H=1.0x10^{-3} cm^{-3} out to at least 35 kpc, kT=0.3 keV
- Consistent with group mass (10^{13} M_{solar} – see Woodley et al 2006) and ram pressure stripping of cold gas from dwarf galaxies (Bouchard et al. 2007)



Cen A as normal early-type galaxy

- Key results
  - LMXB/GC connection – LMXBs preferentially found in densest, most massive GCs
  - Multiple ULXs, similar to GRS1915 (the microquasar) and BH novae in the MW
  - Multi-phase gas still present in the core of Cen A – disturbed by merger or nuclear activity (?)
  - Larger-scale gas does not appear to be in hydrostatic equilibrium
  - Group gas out to at least 30 kpc – probably (much) further

Ongoing/continuing projects

- Existing Data
  - Monitoring of jet knots in radio (VLA) and X-ray (Chandra – HRC GTO), monitoring of the brightest LMXBs – request DDT for significant flaring (ala M87)
  - Characterize thermodynamic state of ISM, large scale gas dynamics, X-ray absorption versus optical extinction in dust lane
  - Ensemble properties of LMXBs (spectral/temporal) + optical IDs
  - Sub-pixel Chandra imaging of jet
- Future Observations with Existing Observatories
  - XMM-Newton Observation of `SML' region – approved, scheduled for mid- July
  - Large scale Suzaku/XMM-Newton survey of group gas
  - Another deep Chandra observation of jet (in later AO) to search for proper motions – deep observation of SW lobe – continuing ACIS-S observations of inner jet – HRC GTO

Future Missions

- IXO – direct measurement of velocity of SW lobe, NML filament, etc., polarimetry of jet, nucleus, and SW lobe, abundance, ionization state, etc. of ISM
- Personal rant – let's not forget imaging! Future imaging mission with 0.1" or better spatial resolution (perhaps with diffractive optics?) would be amazing! Let's look at jet knots, SW lobe shock, etc.!

Outstanding Questions from an Observational Perspective

- Constraints/discussion of elemental abundances – particularly important for ISM studies
- Optical/IR counterparts (stellar or otherwise?) to any of the features in the jet or counter jet
- Distribution of cold ISM – relationship to NML filament
- Detection of synchrotron shock around SW lobe in UV/ optical/IR band
- Latest radio maps of NML
- Ionized gas features associated with jet and/or inner lobes
- Optical/IR (non-GC) counterparts to compact binaries
- Link between jet/lobes/active nucleus and hard X-ray/ gamma ray emission

Finis

- The Bullet Cluster is the most interesting cluster in the Universe – Maxim Markevitch – many times
- Cen A is the most interesting object in the Universe – me - today