Preliminary Results from a Deep (600 ks) *Chandra* Observation of Centaurus A

R. Kraft[1], M. Hardcastle[2], A. Jordan[3], G. Sivakoff[4], D. Worrall[5], M. Birkinshaw[5], D. Evans[1], J. Croston[2], M. Gilfanov[6], R. Voss[6], W. Forman[1], C. Jones[1], P. Nulsen[1], S. Murray[1], C. Sarazin[7], A. Juett[7], S. Raychaudhury[8], N. Brassington[1], W. Harris[9], K. Woodley[9]

1-Harvard/Smithsonian Center for Astrophysics 2-University of Hertfordshire 3-ESO 4-The Ohio State University 5-University of Bristol 6-MPA 7-University of Virginia 8-Birmingham University 9-McMaster University

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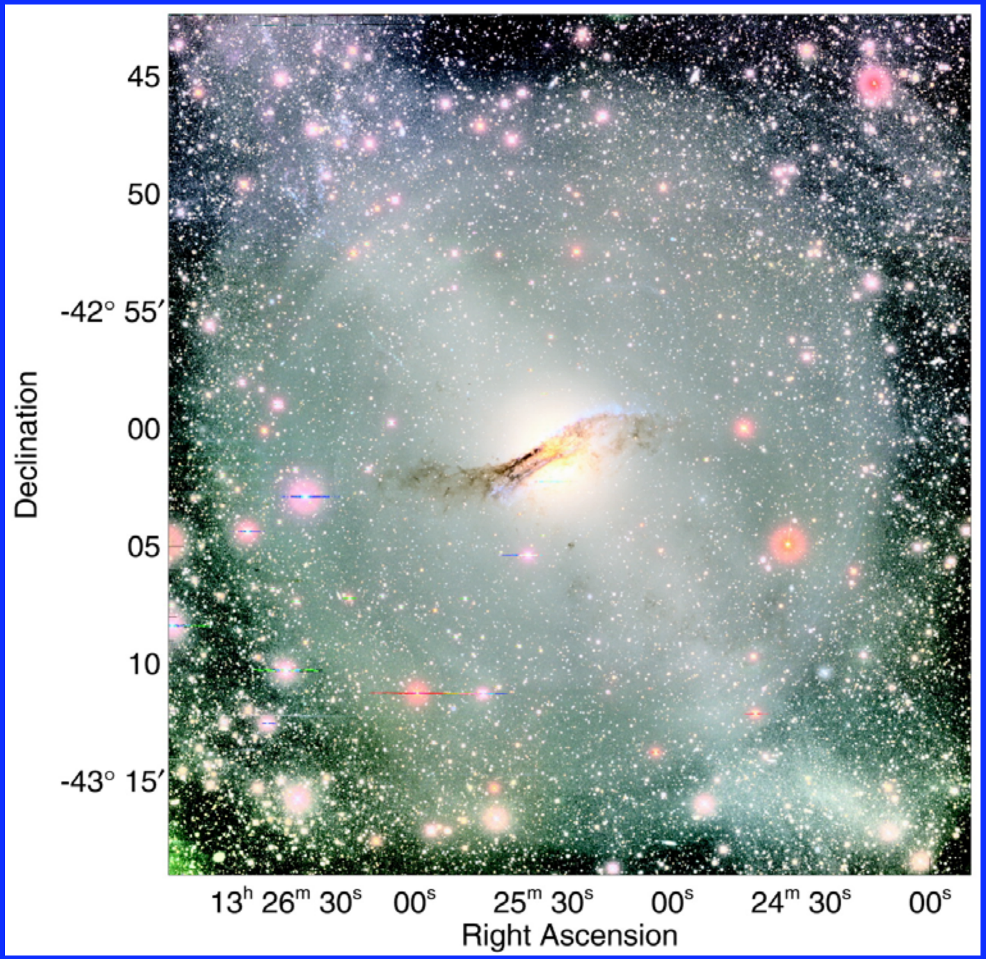
Outline of Talk

- Introduction – Background on Cen A/NGC 5128 and Overview of *Chandra* (and XMM/Newton) Observations
- Science Topics – Emphasis on VLP Results
  - X-ray Binaries and LMXB/GC Connection
  - X-ray Jet
  - Hot ISM and the Interaction between Radio Bubbles and ISM
- Summary and Conclusions

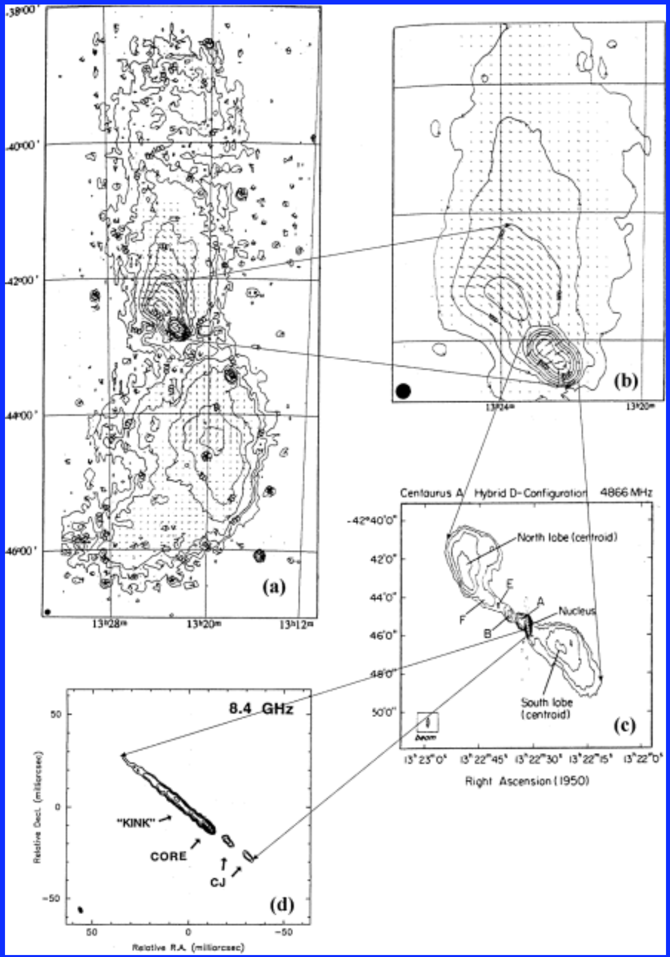
Centaurus A – Fast Facts

- Nearest (3.8 Mpc, 1'=1.105 kpc, 1''=18.4 pc, Woodley *et al*. 2007) massive (M_B=-21.1) elliptical galaxy – five times further than M31, five times closer than the Virgo Cluster
- Prototypical example of several classes of astrophysically interesting objects:
  - Early-type galaxies
  - Late stage mergers (merged with a small spiral 10^9 yrs ago)
  - Low power (FR I) radio galaxies
  - AGN ($L_x=6\times10^{41}$ ergs s^{-1})
  - Dominant member of poor group (M83 is the only other reasonably massive member of the group) – gas poor

Optical Image of Cen A (ESO)



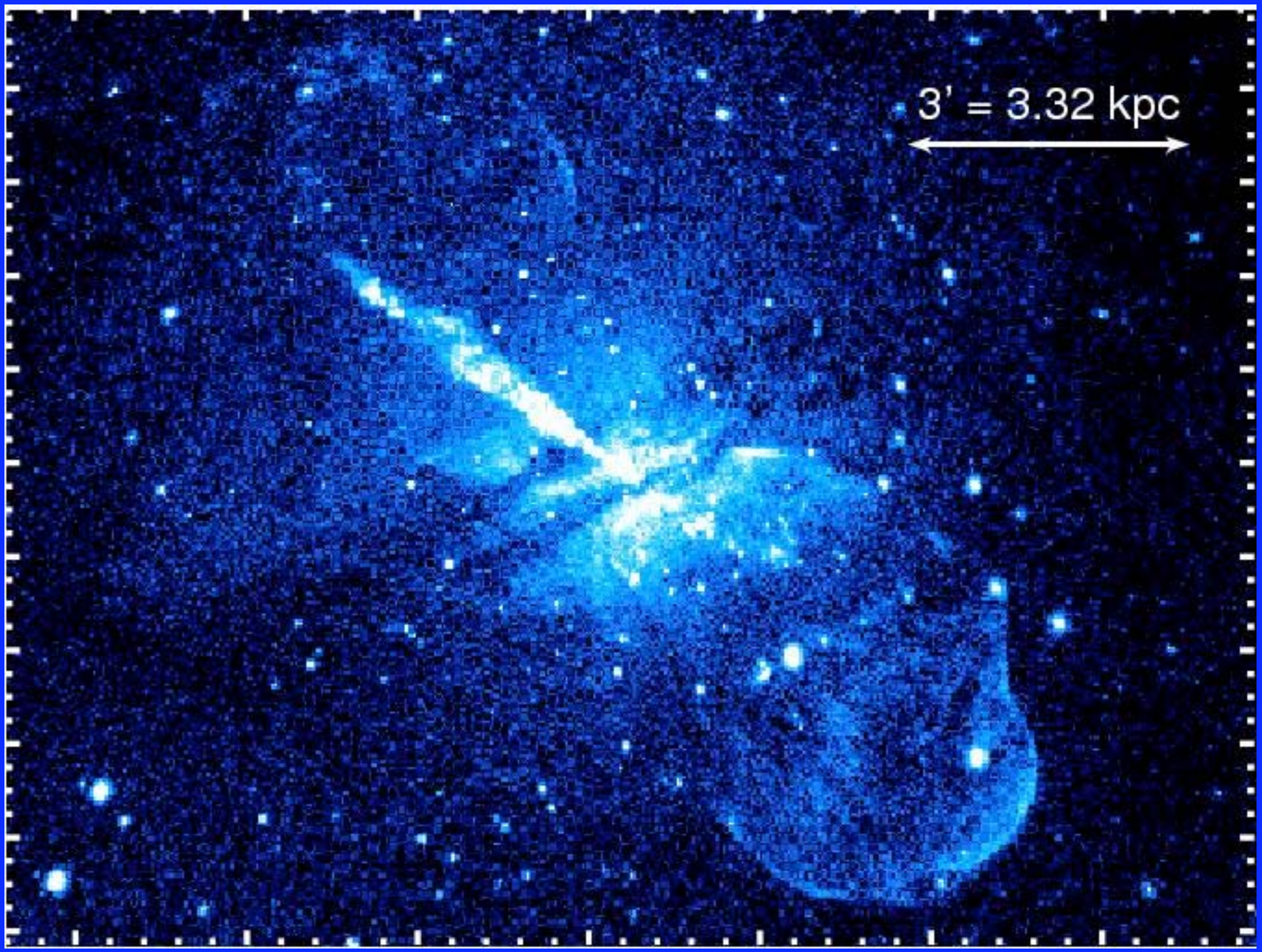
Multiscale Radio Emission from Cen A (Morganti *et al*. 1999)



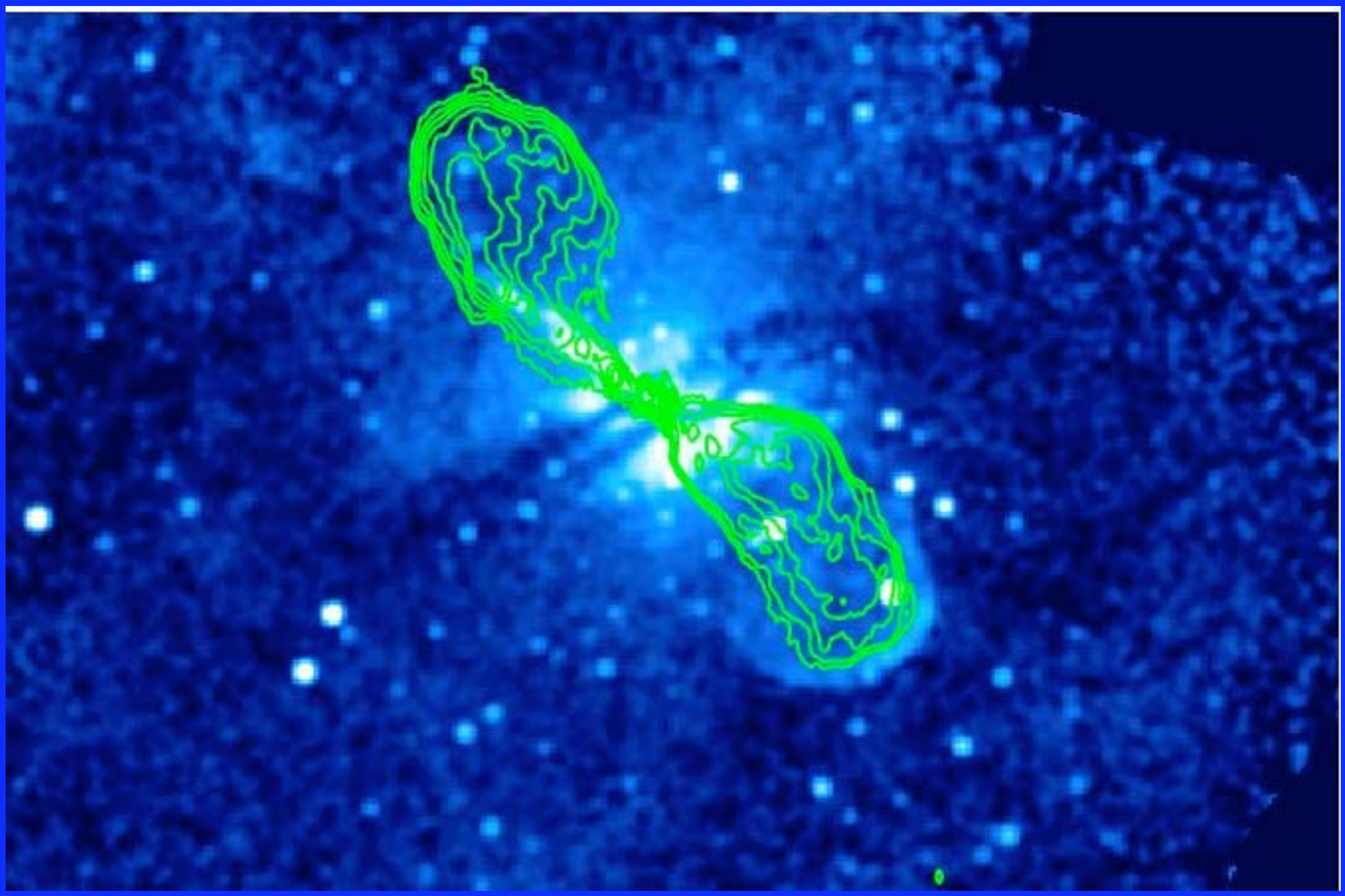
Chandra and XMM/Newton Observations of Centaurus A

- 2 37 ks ACIS-I observations in AO-1
- 2 50 ks HETGS observations of the nucleus in AO2
- 1 50 ks ACIS-S observation in each of AO-3 and 4
- 6 100 ks ACIS-I observations in AO8 (March through June of this year) – Cen A VLP
  - Background extremely low – less than 5% of our data was filtered because of background flaring.
  - All ten imaging data sets have been reprocessed consistently and coaligned. We estimate relative alignment at tens of milliarcseconds and absolute alignment at 0.1''.
- 1 40 ks XMM/Newton observation of central region, and a second 40 ks observation of the Northern Middle Radio Lobe

623 ks of ACIS-I observation in the 0.5-2.0 keV band



Gaussian smoothed, exposure corrected image of Cen A in the 0.5-1.0 keV band

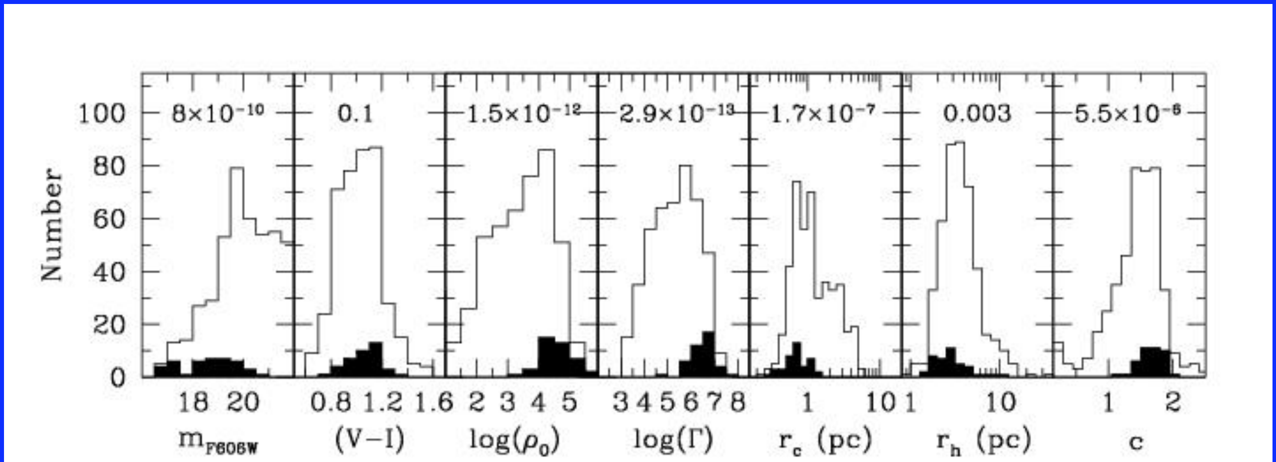


General Properties of X-ray Binary Population of Cen A

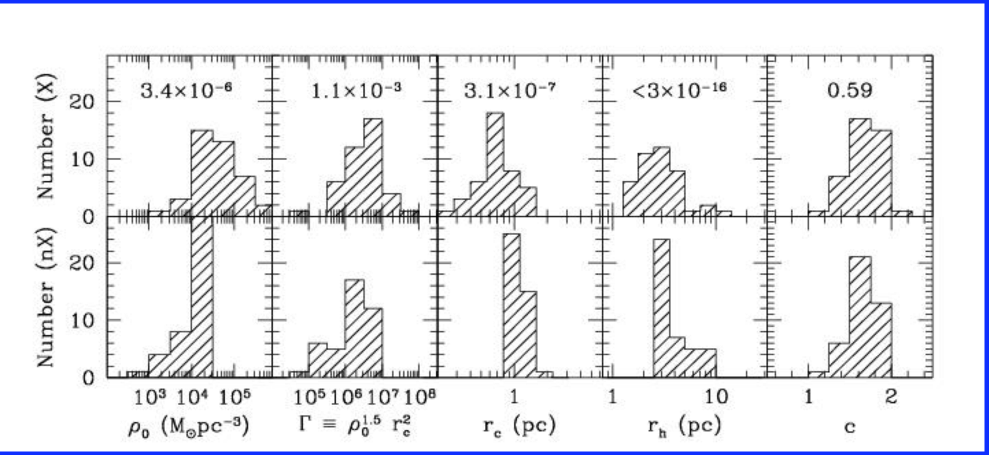
- We've detected roughly 700 point sources in the combined data sets.
- There are roughly 100 LMXBs in Cen A with $Lx>10^{37}$ ergs s^{-1}, or 250 counts in the 0.5-5.0 keV band.
- The faintest source has $Lx=3x10^{35}$ ergs s^{-1} (0.1-10 keV band). The observations are complete and unbiased (defined as a 4 sigma measurement of the luminosity) above an X-ray luminosity of $1.5x10^{36}$ ergs s^{-1}.
- One transient ULX was detected in the earlier observations (Kraft et al. 2001, Ghosh et al. 2006), and a second (previously unknown) ULX ($Lx=3x10^{39}$ ergs s^{-1}) detected in all 6 VLP observations. There are two additional (previously unknown) transients with $Lx>10^{38}$ ergs s^{-1} detected in the VLP observations.
- One of the primary science goals of the VLP was to combine the deep Chandra observations with a wide field HST/ACS survey of the GC population. **All** our optical data were taken just before the demise of the ACS!
- We are in the process of determining the positions, spectral parameters, and temporal properties of all the bright sources. Quick and dirty time series analysis finds no obvious features (eclipses, pulsations, bursts, flares, etc.) in the lightcurves of any source not known to be a foreground star. We will use the ACS and extensive ground based data to optically identify (as foreground star, background AGN, or massive companion in Cen A) as many of the point sources as possible.

The LMXB/GC connection in Cen A

- HST/ACS observations were used to determine structural parameters of Cen A GC population in the central region of the galaxy. Cen A is close enough so that the core properties of GC can be resolved with HST. This cannot generally be done for galaxies at the distance of Virgo.
- From ground based GC studies, we find that an LMXB in a Cen A GC is three times more likely to be hosted by a red, metal rich GC rather than a blue, metal poor GC (Woodley et al. submitted), consistent with several other studies (Kundu et al. 2003 and others).
- We found 440 GC candidates (in 21 HST fields with F606W filter), of which 43 host LMXBs.
- Graph below shows distributions of optical magnitude, color, central density, encounter rate, core radius, half-light radius, and concentration parameter for GC with (black) and without (histogram) LMXBs. The number at the top is the probability that the two sample distributions are drawn from the same parent distribution.
- LMXBs are most likely to be formed in GCs that have high central densities and high encounter rates.



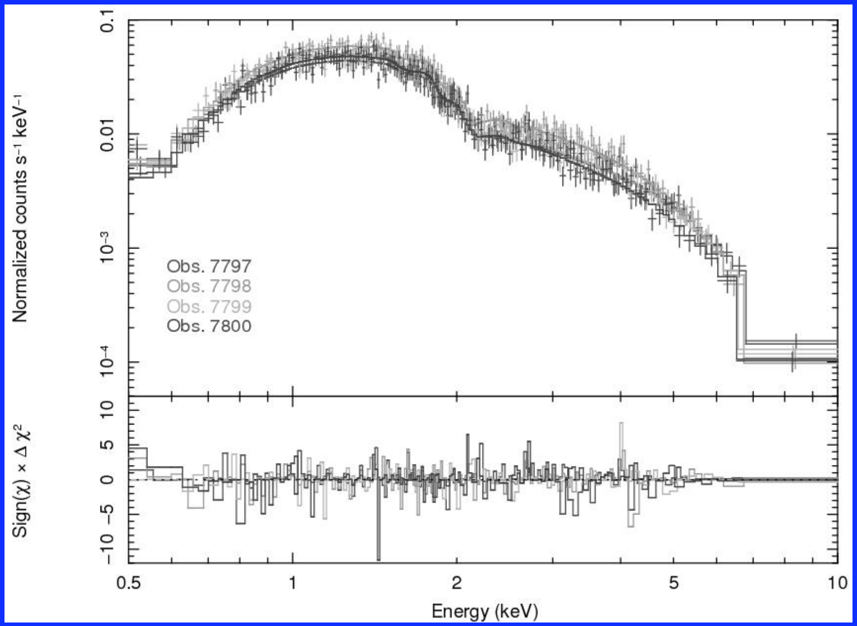
What parameters of the GC are important in determining whether it will contain an LMXB?



- Top row – GC parameters for GCs that contain LMXBs
- Bottom row – subset of GCs that do not contain LMXBs with same mass distribution as the first set.
- The parameters of central density, encounter rate, core radius, and half-light radius are, after removing the effect of GC mass, important for determining whether a GC has an LMXB.
- The concentration parameter is not important for determining whether a GC contains an LMXB when comparing distributions of GCs with similar mass distributions.
- Smaller sizes and denser cores are the fundamental drivers of whether a GC contains an LMXB.

Properties of the Newly Discovered ULX - CXOU J132518.3-430304

- X-ray luminosity of 3×10^{39} ergs s^{-1}. Undetected in all previous Chandra observations ($L_x < 10^{36}$ ergs s^{-1}).
- Outburst timescale at least 70 days. No evidence of short timescale variability (pulsations, eclipses, etc.).
- Spectra well described by a power law plus disk blackbody with intrinsic absorption (tentative – pileup). No evidence of Fe K line or other narrow spectral features. Flux dominated by PL component (photon index 2.1).
- Probably a black hole transient in the hard state.
- There are now two short/intermediate timescale transients detected in Cen A, and none in M87 and NGC 1399, two elliptical galaxies roughly 4 times more massive than Cen A. None of the luminous X-ray sources in these galaxies are transients (Irwin et al. 2006). This suggests some fundamental difference between Cen A and M87/NGC 1399.

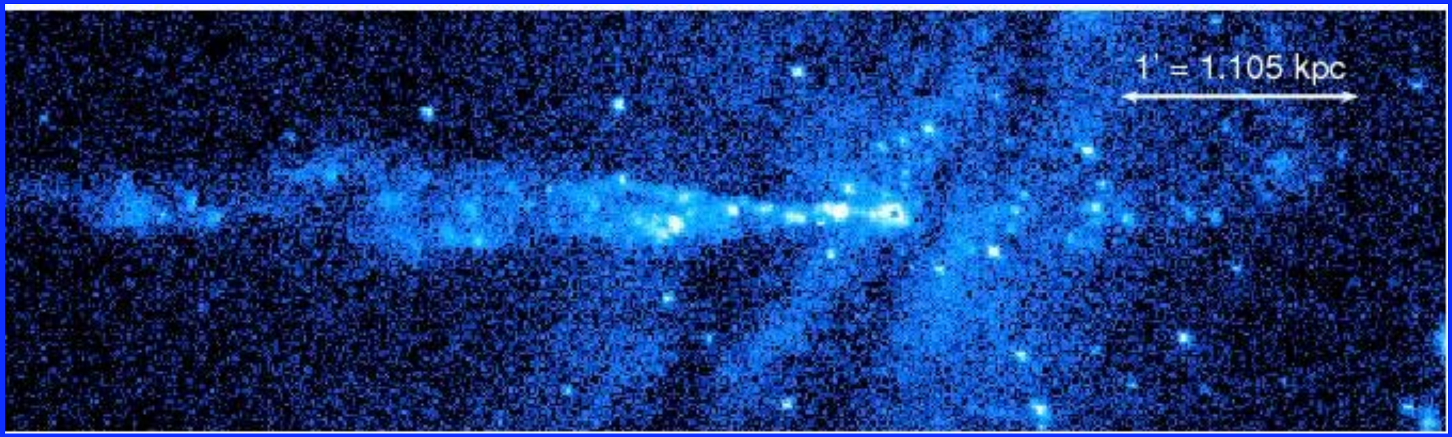


X-ray Jet

- Prime science goal of the VLP was to create a deep image of the jet at the energy loss scale of the X-ray synchrotron emitting electrons (timescale is tens of years for equipartition magnetic fields).
- Cen A is the ONLY extragalactic object in which Chandra’s spatial resolution probes this scale.
- Goal is to create an X-ray spectral index map of the jet on small scales. There was a cottage industry of people doing this for radio jets with the VLA in the 1980s, but this is the first time this has been done in the X-rays.
- Secondary goal include search for proper motions of the X-ray knots, structure of the kpc-scale counterjet, constraints on thermal gas swept up by Kelvin-Helmholtz instabilities, and detection of faint knots.

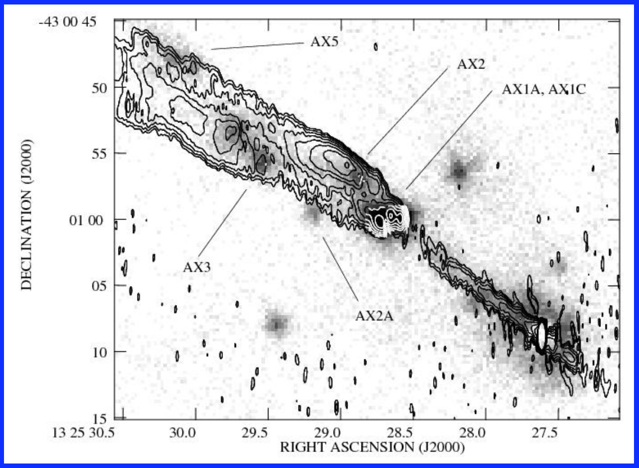
X-ray Image of Cen A Jet

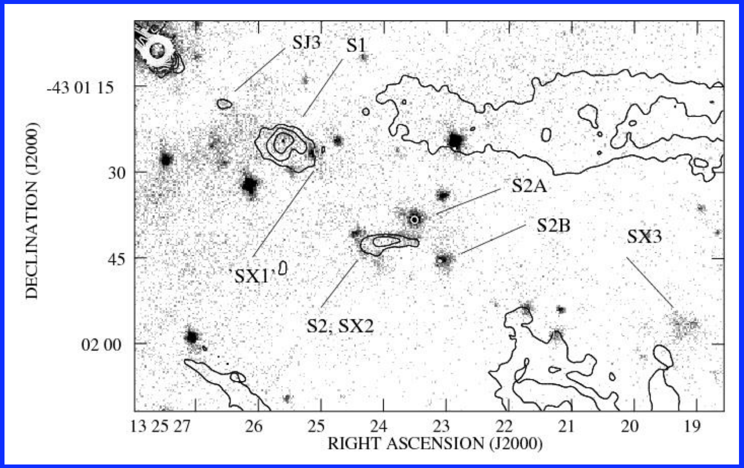
- X-ray emission from jet believed to by synchrotron radiation from a population of ultrarelativistic particles.
- Previous observations resolved jet into approximately 30 discrete knots surrounded by diffuse X-ray emission.
- Spatial offsets found between X-ray and radio peaks.
- Proper motions of RADIO knots found in monitoring observations by the VLA.
- X-ray spectrum generally well described by a steep (photon index 2.0-2.5) absorbed power law.



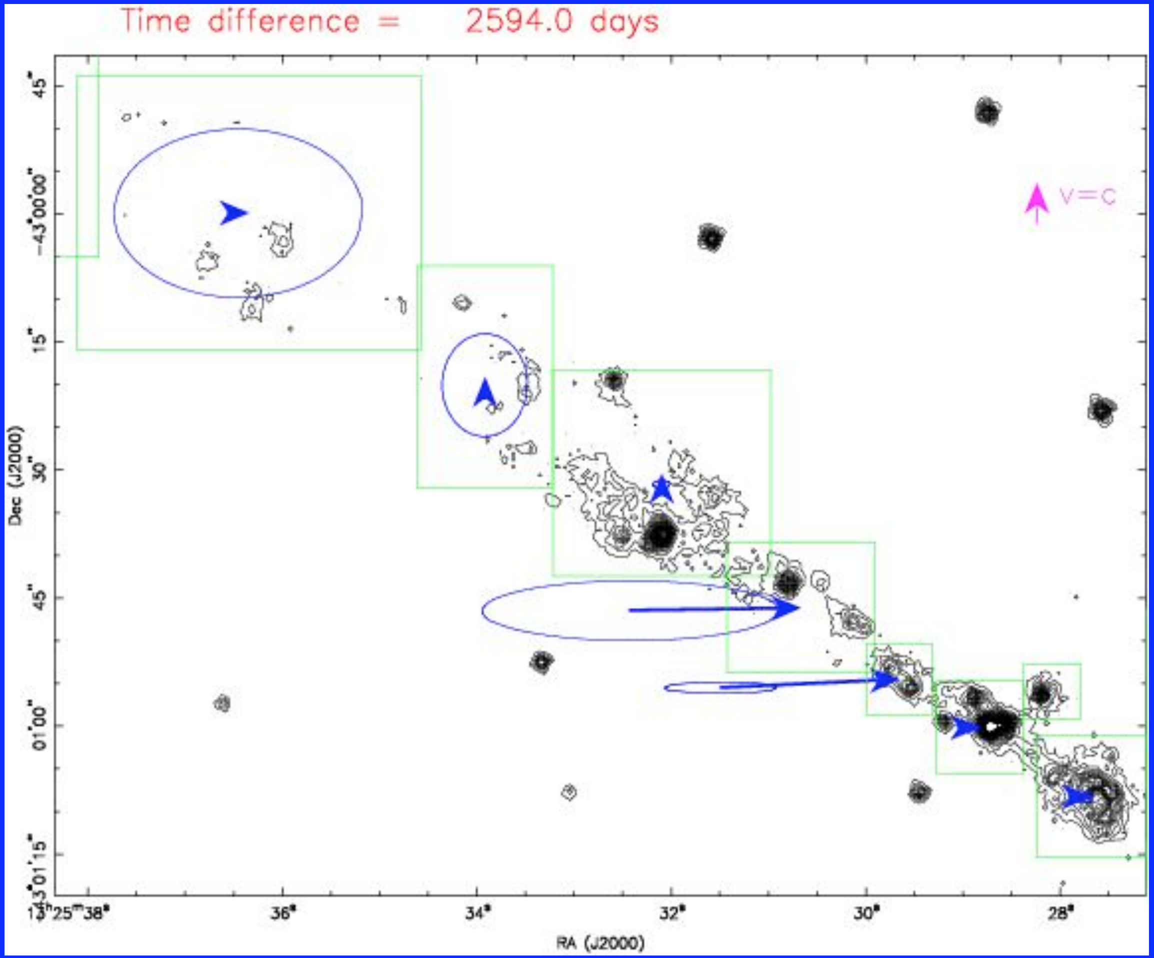
Results

- The inner part of the jet is dominated by knotty, relatively flat spectrum, features and is consistent with particle acceleration at discrete shocks.
- Beyond the central kpc, the emission from the jet is dominated by diffuse emission with a steeper spectrum than the knots. This suggests that some unknown diffuse shock mechanism is accelerating the electrons.
- We detect diffuse structures up to 1.8 kpc from the nucleus in the counterjet direction. Whatever is happening in the forward jet is also occurring in the counterjet.
- Temporal variation of the knots over the 8 year baseline is small (10% variations in flux). There are no dramatic intensity or spectral variations in any of the knots similar to that seen in M87.
- The spectrum along the periphery of the jet is steeper than in the center. This is contrary to the simple sheath/spine model in which all of the X-ray synchrotron emission comes from a thin sheath that surrounds the fast moving spine and protects it from interacting with the ambient medium.



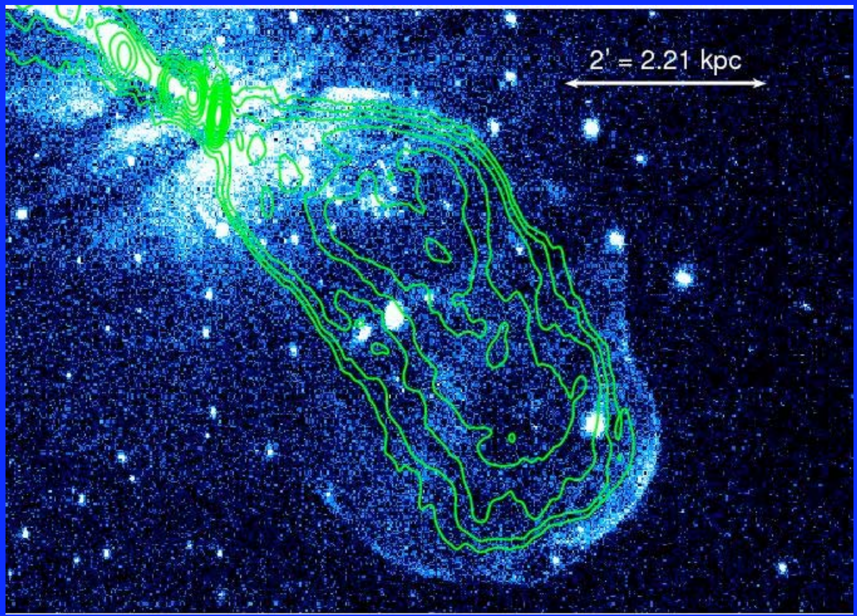


Cross-correlation of AO1 data with AO8/VLP data



Southwest Radio Lobe

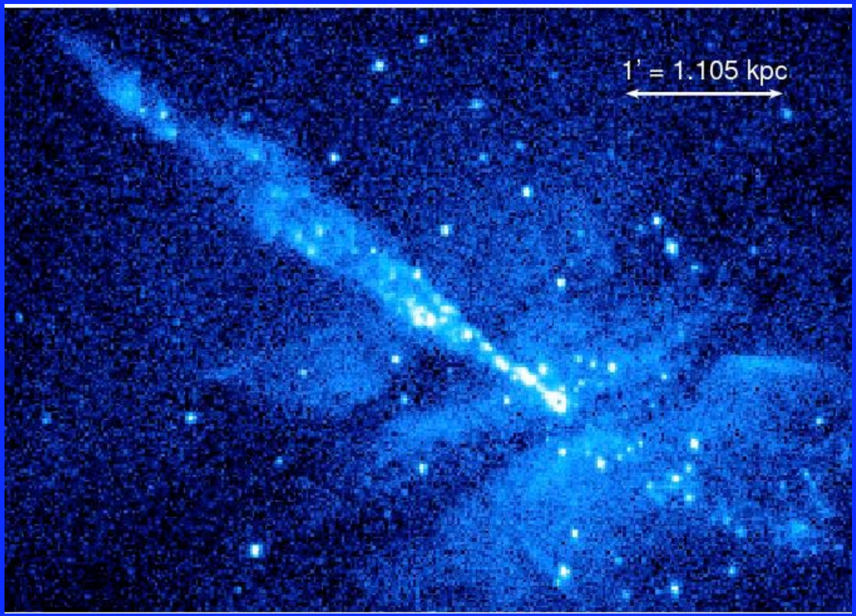
- Shell of shock heated gas (3.5-4.0 keV) surrounding the radio bubble – the lobe is driving a strong shock (Mach number = 8) into the ISM (0.3-0.5 keV). If only a small fraction of the shock energy is distributed through the ISM, it (the ISM) will be blown out of the galaxy.
- If the shock-heated plasma is collisional, the electrons will not have equilibrated with the protons and the shock will be even stronger (see Kraft et al. 2007).
- Simulations and analysis of cluster mergers, lobe/ICM interactions, etc. almost always assume pure hydro. The temperature structure of the shock-heated shell may allow us to put strong constraints on the validity of this assumption (transport processes). Comparable to deep observations of Galactic and Magallenic SNRs.
- One of the surprises of the VLP observation is that the shock is detached from the lobe along the SE periphery. This suggests some complex gas motions of the ambient ISM.



Merger Dynamics and Interaction between ISM and Radio Lobes

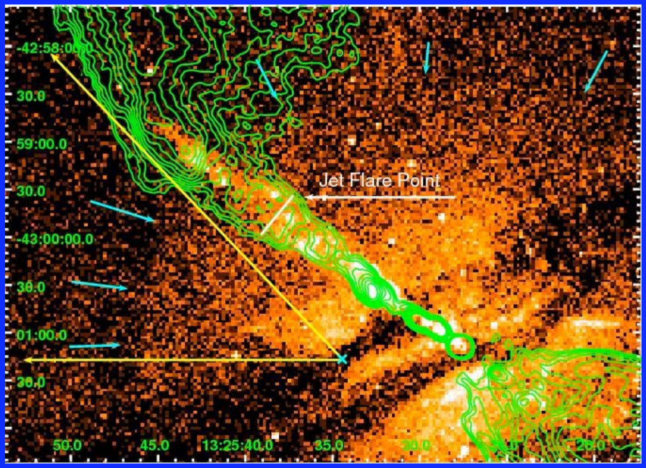
- Deep Chandra observations of the Antennae, probably the best example of an early stage galaxy merger, show large variations in temperature and elemental abundance of the gas, as well as regions of enhanced star formation (Baldi et al. 2006, among others).
- A survey of Chandra observations shows a complex evolution of the X-ray luminosity of merging galaxies as a function of time since merger (Brassington et al. 2006).
- Cen A is the ideal target to study the gas dynamics of a late stage merger. What is the temperature and entropy distribution of the gas in the late stages of the merger? How well are the metals mixed?
- Cen A has also undergone several epochs of radio outbursts. Observation of the gas also gives unique insights into the dynamics and evolution of the interaction of the radio plasma with the hot ISM.

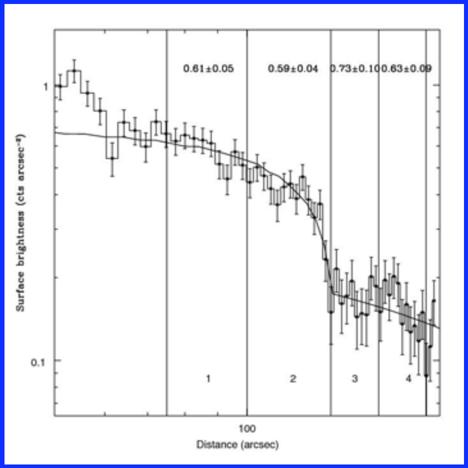
Complex Morphology of ISM to the NE of the nucleus



- There are several sharp surface brightness discontinuities in the gas, perhaps indicative of gas motions and regions of overpressure.
- Most of these are not obviously related to the nuclear outflow, and are thus probably related to the merger. After 1E9 years, the gas in the central part of the galaxy has not relaxed.
- Complex absorption seen, as well as X-ray filament to the NW (Karovska et al. 2003).
- One discontinuity extends in an 120 degree arc about 3' (3.3 kpc) from the nucleus.
- Temperature of the gas in the central regions varies from 0.3 to 0.6 keV, with some spectral fits requiring an additional cooler (0.15 keV) component. Elemental abundance is generally poorly constrained (Brassington, Ph. D. thesis 2006).
- We are in the process of fitting spectra on small (few arcsecond) scales in the VLP data to create a temperature map. We will also compare X-ray derived column densities with extinction maps of the dust lane to determine A_V/N_H.
- Even 1 billion years after the merger, the central regions of the galaxy are a turbulent place!

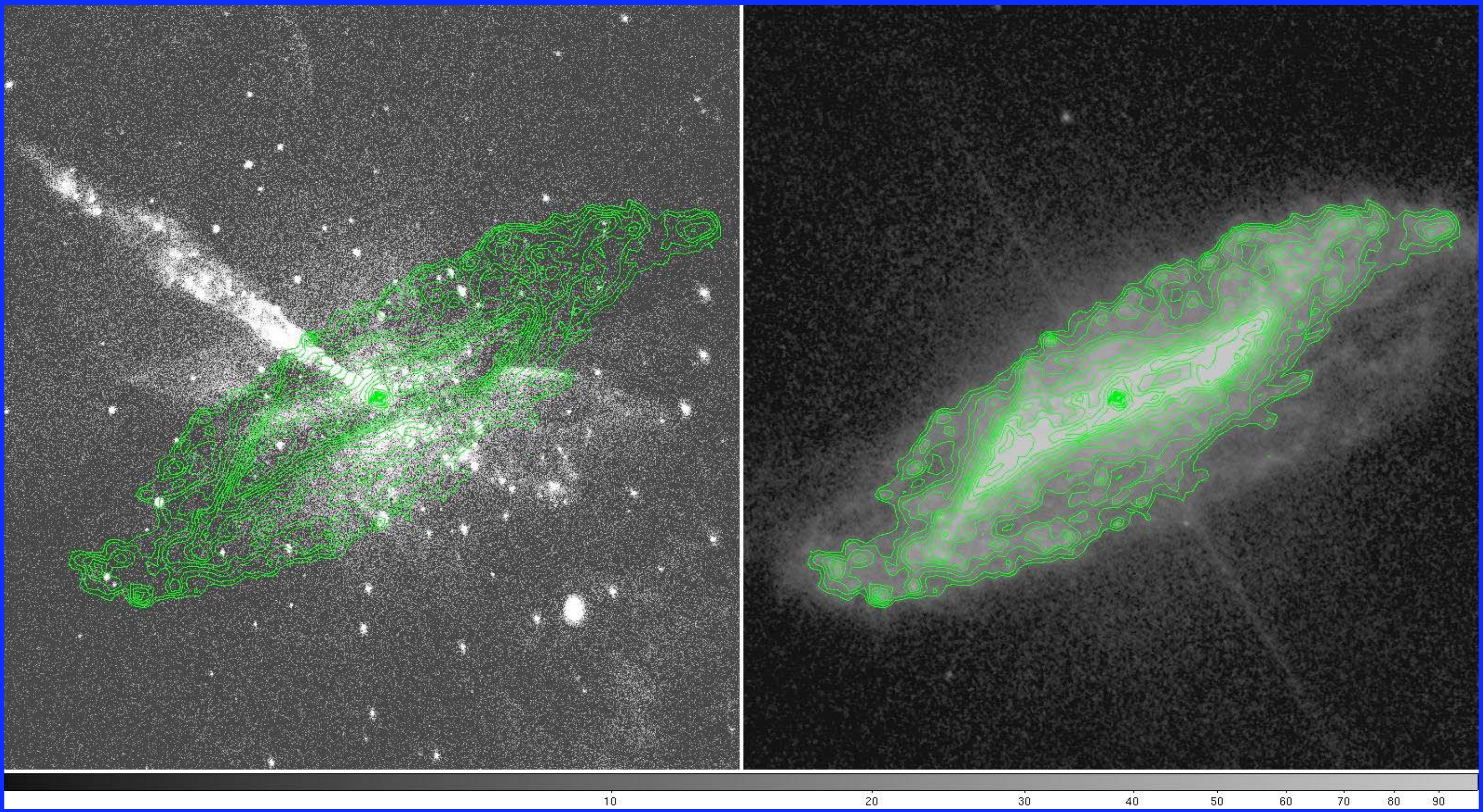
X-ray Surface Brightness Discontinuity





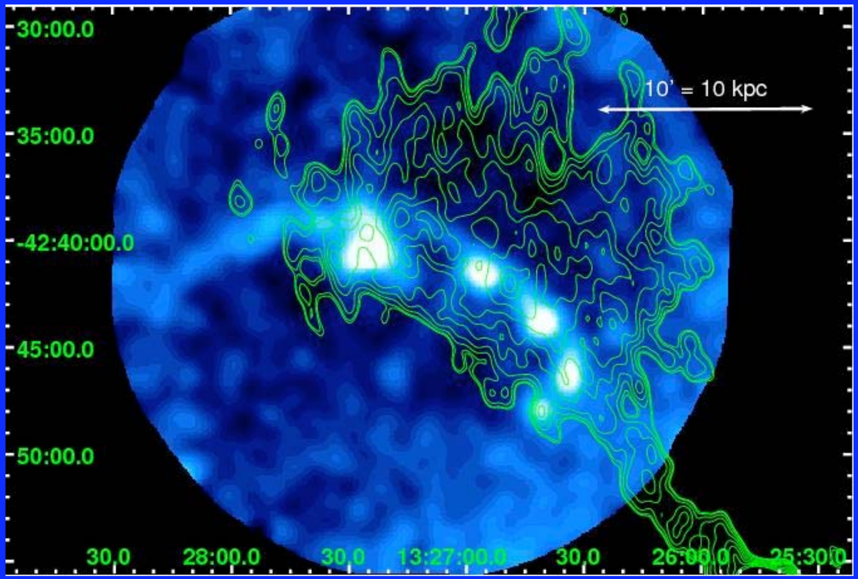
- Fit surface brightness profile with constant density interior to discontinuity and beta-model profile exterior.
- If the elemental abundance is the same, the density of the interior gas is roughly 2.5 times larger than the exterior gas. This implies that there is a large (factor of 7) jump in the elemental abundance.
- Gas could be moving to the NW. The density jump could be the cause of the jet disruption, and ram pressure of gas is pushing lobe to the NW.

Raw X-ray Image (0.6-2.6 keV) with Spitzer (IRAC4) contours overlaid



Northern Middle Radio Lobe –XMM/Newton (MOS) image with radio contours overlaid

- X-ray filament coincident with southeast boundary of NML.
- Emission is definitely thermal, perhaps from gas entrained as the bubble has risen buoyantly (thermal gas trunk – Saxton et al. 2003).
- Gas density (nearly 10^{-2} cm^{-3}) is much larger than ambient gas, and thermal pressure much larger than equipartition pressure of the lobe.
- How did the gas get there? What is holding it there? Why doesn't it burst out of the lobe and fall back to the center (or expand and equilibrate with the ambient gas)?



Summary and Conclusions

- We find that central density and encounter rate are the two most important parameters in determining whether a GC contains an LMXB.
- A second bright ULX has been discovered in our VLP observations. It is probably a black hole transient. There are a large number of short/intermediate timescale transients in Cen A relative to the other nearby massive elliptical galaxies M87 and NGC 1399.
- We will ultimately publish a detailed catalog of point sources including spectra, positions, temporal properties, optical IDs, etc.
- The bright knots of the jet have a harder spectrum than the diffuse emission. There is also evidence that the emission from the knots on the periphery of the jet have a harder spectrum than those on the interior..
- Cross-correlation of the AO1 data with the VLP data demonstrates large scale motions in the jet and possible expansion of some of the knots.
- The shock is detected along the entire periphery of the SW radio lobe, although it is detached along the southeast boundary of the lobe. We MAY be able to make a detailed study of the transport properties of the gas behind the shock.
- We detect multiple sharp features in the ISM indicative of discontinuities in density (and perhaps pressure) and/or elemental abundance. One of these is perhaps responsible for the disruption of the forward jet and the creation of the NE radio lobe.
- The X-ray filament associated with the Northern Middle Radio Lobe first observed with *Einstein* is hot gas, probably entrained as the bubble has risen buoyantly.
- Six Letters are currently being written (two in press, two submitted, the other two to submit later this month):
  - Hardcastle et al. 2007 – Spectral index map of the jet and X-ray morphology of the counter jet
  - Jordan et al. – LMXB/GC connection
  - Sivakoff et al. – Spectral and temporal properties of the ULX
  - Worrall et al. – Lateral Spectral Variations in the X-ray Jet
  - Kraft et al. – Radio bubbles in a crosswind
  - Birkinshaw et al. – Cross correlation of multiple epochs of Chandra observations of the Cen A Jet