PROBING RELATIVISTIC PLASMAS IN SUPERNOVA REMNANTS, RADIO GALAXIES, AND CLUSTERS AT LONG RADIO WAVELENGTHS

N. E. Kassim
Naval Research Laboratory
4555 Overlook Ave. SW, Washington, DC 20375-5351 USA
NAMIR.KASSIM@NRL.NAVY.MIL
T. J. W. Lazio, W. M. Lane, A. S. Cohen
JOSEPH.LAZIO@NRL.NAVY.MIL, WENDY.LANE@NRL.NAVY.MIL, AARON.COHEN@NRL.NAVY.MIL
T. Clarke, C. L. Brogan, R. A. Perley
TC4G@ASTSUN.ASTRO.VIRGINIA.EDU, CBROGAN@IFA.HAWAII.EDU, RPERLEY@NRAO.EDU

Abstract

High resolution ($< 1'$), low frequency (< 100 MHz) radio observations of non-thermal sources such as supernova remnants (SNRs), radio galaxies, and clusters can be a valuable complement to both higher frequency radio and X-ray observations. For SNRs they probe unshocked ejecta, constrain the physics of Fermi acceleration processes, and delineate the distribution of ionized gas at SNR/molecular cloud boundaries, all of which are well complemented by X-ray observations. For radio galaxies they provide sensitive continuum spectra for studying radio galaxy evolution, for understanding self-absorption processes, and for delineating the extent of low surface brightness emitting regions that may not be revealed by higher frequency radio observations. Toward clusters they anchor accurate continuum spectra that enable studies of the pressure balance between the non-thermal plasma in the constituent radio sources and the confining thermal X-ray emitting gas, and they are sensitive to the buoyant bubbles of relativistic plasma rising to cluster peripheries. In all cases the unrivaled continuum spectra can be utilized to understand the details of shock acceleration processes that may have their seed particles in the X-ray emitting thermal gas. Here we provide examples of the ongoing Very Large Array-led renaissance in high resolution, low frequency radio astronomy that is providing images that can address these questions. These observations foreshadow the rich scientific landscape awaiting exploration by an emerging generation of much more powerful low frequency instruments such as the Low Frequency Array (LOFAR) and the Long Wavelength Array (LWA).

1 Introduction

Sub-arcminute resolution, long wavelength radio observations of non-thermal sources including supernova remnants (SNRs), radio galaxies, and clusters are a powerful complement to both higher frequency radio and X-ray observations. However, until recently the past limitation in the angular resolution and sensitivity of low frequency radio imaging, particularly below 100 MHz, has precluded its availability for the detailed study of astrophysical sources. The Very Large Array (VLA) is finally providing the radio observations to do this, and here we provide examples in which these new images are being utilized for studies in both Galactic and extragalactic sources.

2 First 74 MHz imaging with the VLA + Pie Town link

A 74 MHz receiver has been added to the Pie Town VLBA antenna, bringing the full resolving power of the VLA + Pie Town link to this lowest VLA frequency. With baselines up to 73 km, Fig. 1 shows the first images emerging from this system. At a higher resolution then any previous imaging below 100 MHz, these maps mark another important milestone in low frequency radio astronomy. For comparison, 330 MHz images are also shown. These images are being used

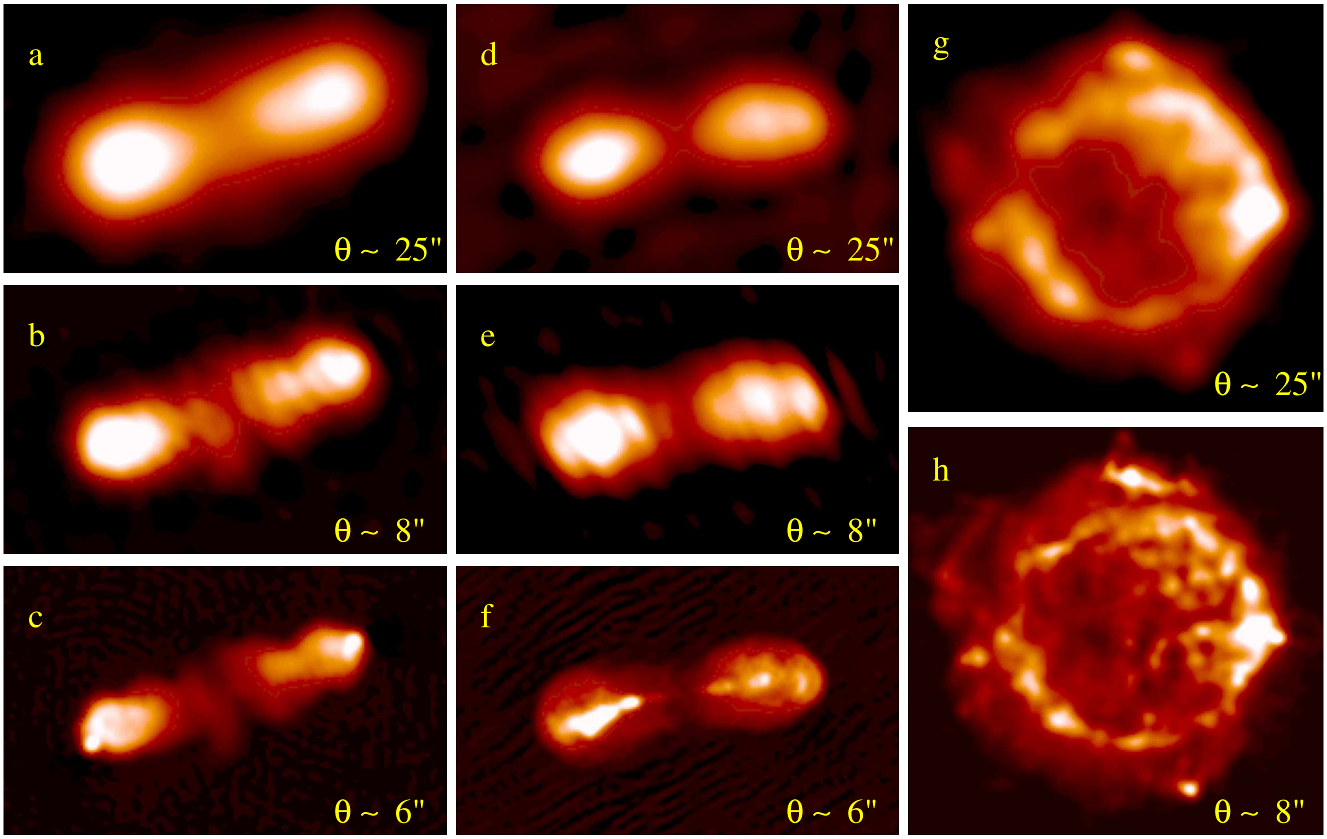

Figure 1: (a) Cygnus A at 74 MHz with VLA A-configuration
(b) Cygnus A at 74 MHz with VLA + Pie Town Link
(c) Cygnus A at 325 MHz with VLA A-configuration
(d) Hercules A at 74 MHz with VLA A-configuration
(e) Hercules A at 74 MHz with VLA + Pie Town Link
(f) Hercules A at 325 MHz with VLA A and B configurations
(g) Cassiopeia A at 74 MHz with VLA A-configuration
(h) Cassiopeia A at 74 MHz with VLA + Pie Town Link
Cygnus A images courtesy of R. Perley, private communication, Hercules A images are from Gizani et al. (2004) and Cassiopeia A images are courtesy of T. Delaney, private communication.

to study evolution (e.g., via synchrotron aging) and self-absorption processes (e.g., via synchrotron self-absorption) in radio galaxies Cygnus A (Kassim et al., 1996, 2004) and Hercules A (Gizani et al., 2004), and for studying shock acceleration and ejecta in the SNR Cassiopia A (Cas A) (Delaney et al., 2005).

3 Studying shock acceleration and ejecta in supernova remnants

Radio spectral index maps are powerful tracers of physical processes in SNRs–if they are of sufficient accuracy. Historically, however, such maps have had a limited frequency dynamic range, caused primarily by the lack of good low frequency maps. Figure 2 illustrates these difficulties by comparing spectral index maps between 330 and 1400 MHz and between 74 and 330 MHz. In the former (angular resolution $\sim 7''$) subtle variations trace shock acceleration related processes; in the latter (angular resolution $\sim 25''$) only a much more crude spectral flattening (blue), likely tracing absorption from cool, unshocked ejecta, is seen.

Figure 3 illustrates a connection between radio and X-ray observations of Cas A. A high angular resolution ($\approx 9''$) 74/330 MHz radio spectral index map afforded by the VLA+PT Link is compared against continuum dominated X-ray emission from *Chandra*. The typical radio spectral indices seen at higher frequencies are approximately -0.7 to -0.6. The blue indicates re-

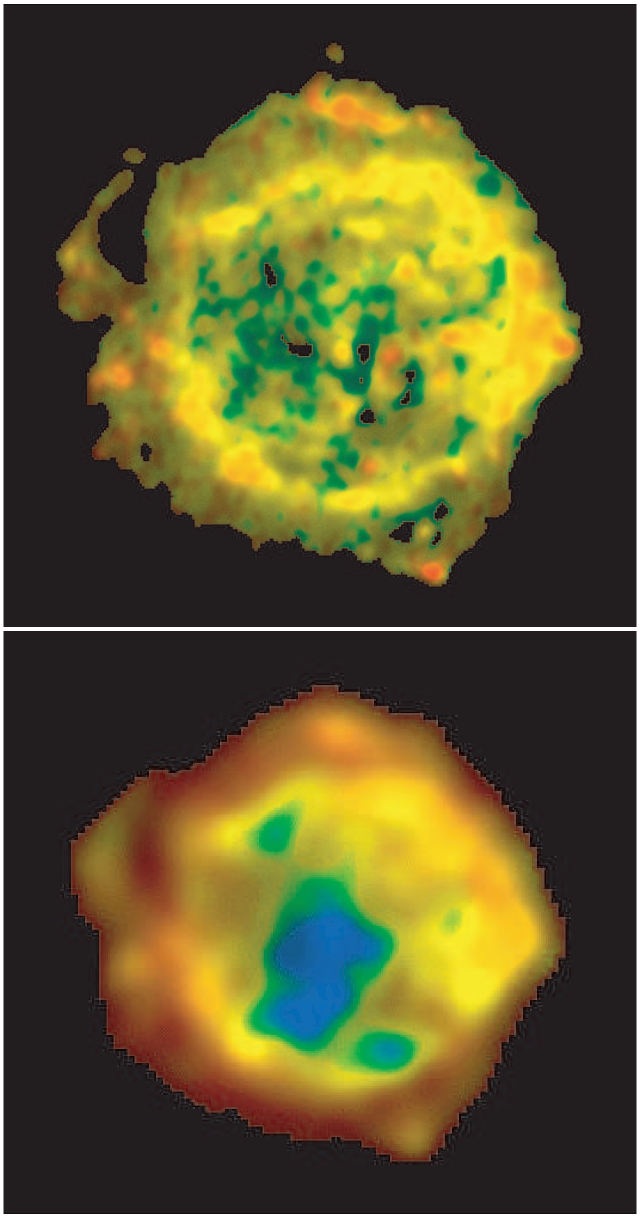

Figure 2: Spectral index maps of Cas A for (a) 330/1400 MHz ($\theta \sim 7''$) and (b) 74/330 MHz ($\theta \sim 25''$). Spectral index α ($S \propto \nu^{\alpha}$) varies from -0.9 (red) to -0.5 (blue).

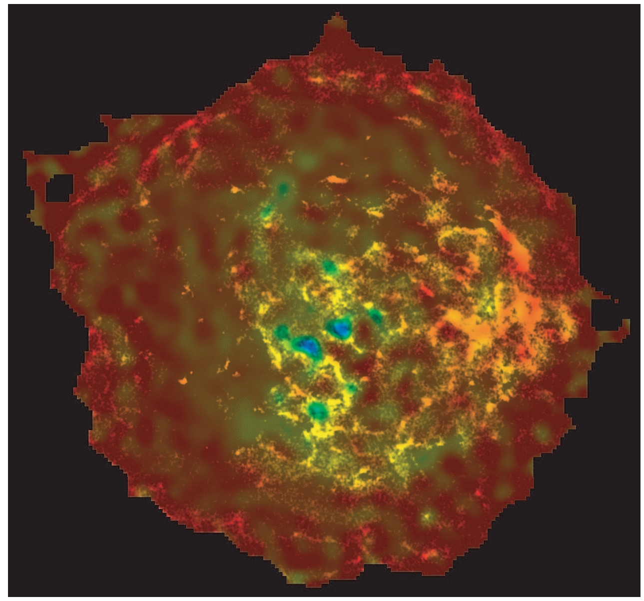

Figure 3: Radio spectral index (color) overlaid on total intensity *Chandra* X-ray intensity (brightness). The radio spectral index varies from -0.9 (red) to -0.35 (blue).

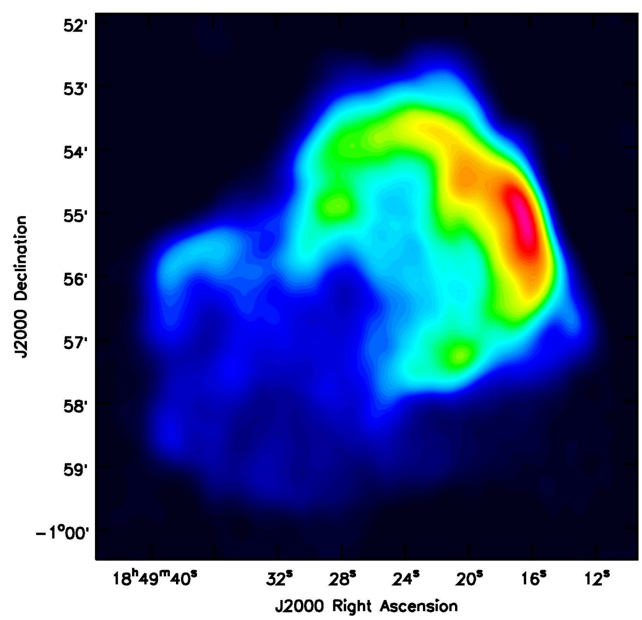

Figure 4: Total intensity 330 MHz radio image of supernova remnant 3C391.

gions with $\alpha \approx -0.35$, thus representing a significant change in spectral index from that observed at higher frequencies. This change may be due to absorption from unshocked ejecta since it is localized toward the interior of the remnant. Much of the very flat spectral indices are also associated with the "interior" X-ray continuum-dominated emission likely associated with the forward shock. The greater absorption toward these filaments may indicate that they are on the far side of the remnant. The results presented here are drawn from the paper presented by Delaney et al. (2005).

4 Tracing supernova remnant-molecular cloud interactions

Figure 4 shows a total intensity image of the SNR 3C391.

The four panels in Fig. 5 reveal a multi-wavelength pic-

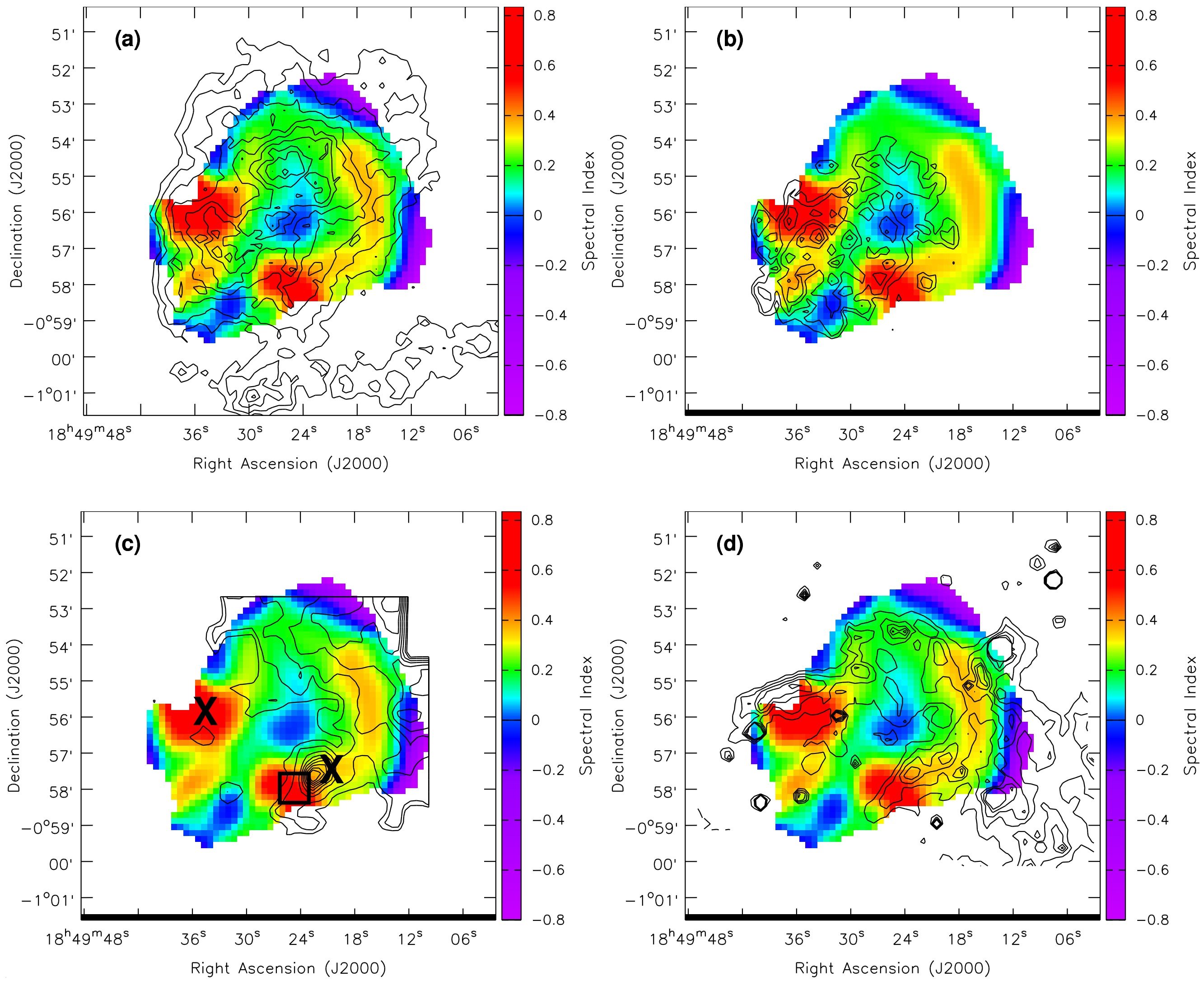

Figure 5: (a) Hard X-ray contours from *ASCA* in the 2.6–10 keV range (Chen & Slane, 2001) superposed on the 74/330 MHz spectral index map. (b) Soft X-ray contours from *ASCA* (Chen & Slane, 2001) in the 0.5–2.6 keV range superposed on the 74/330 MHz spectral index map. For both (a) and (b) the lowest contour is 30% of the peak value. (c) CO (2-1) integrated emission from 91 to 110 km s^{-1} tracing the molecular cloud that is interacting with 3C391 (Reach & Rho, 1999) superposed on the 74/330 MHz spectral index map. The crosses indicate the positions of OH(1720 MHz) masers (Frail et al., 1996) and the squares indicates the position of an ionizing shock detected by Reach et al. (2002). (d) IR emission from ISOCAM at 12–18 μm (Reach et al., 2002) superposed on the 74/330 MHz spectral index map. Notice the impressive agreement between the regions of strongest 74 MHz absorption and the IR emission.

ture of a SNR-molecular cloud (MC) interaction. The color in each frame is 74/330 MHz radio spectral index of the SNR 3C391, with the red and yellow tracing regions of thermal absorption (flat spectrum). Hard X-rays trace the entire SNR (Fig. 4a), while soft X-rays only emerge from the "blow out" side to the southeast (Fig. 5b). The SNR is colliding with a MC to its northwest, as seen in CO (Fig. 5c). Excellent agreement between IR emission (Fig. 5d) and other tracers of ionizing shocks provides striking delineation of the sheath of ionized gas residing in this SNR-MC shock boundary (Brogan et al., 2002).

5 Discovering new cluster halo and relic systems

The number of radio relics and halos has grown rapidly from just a few to several dozens in the past several years. Because of their very steep spectra and diffuse morphology, low frequency observations are an ideal

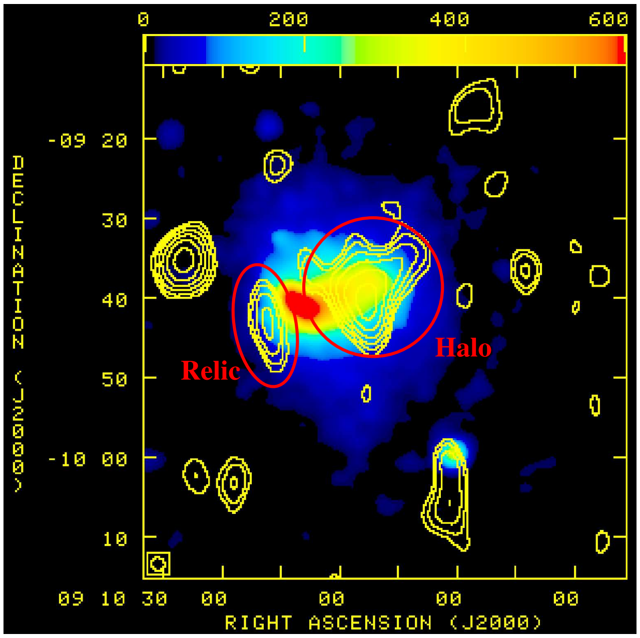

Figure 6: Abell 754. (Color) "Disturbed" *ROSAT* X-ray emission suggesting a recent cluster merger in Abell 754; (Contours) 74 MHz radio emission discovering both a central radio halo and, at the expected shock location, a radio relic (Kassim et al., 2001).

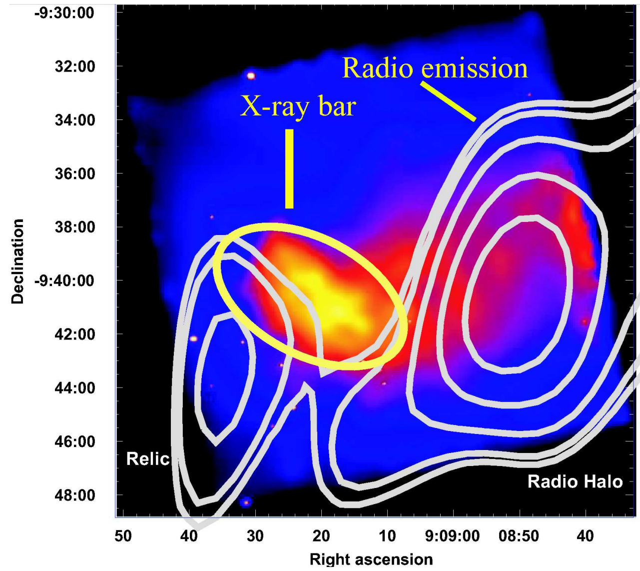

Figure 7: Overlay of *Chandra* ACIS-I 0.3–10 keV X-ray data (color) of the central regions of A754 with 74 MHz radio emission (contours). In addition to a number of compact X-ray sources, the extended thermal emission from the cluster is visible as a broad EW extension. The bright X-ray bar running NE to SW through the image is thought to be the result of ram-pressure from a cluster merger (Clarke et al., 2003).

way to discover such objects. Figure 6 and 7 illustrate radio and X-ray comparisons between the presumed merging cluster A754, within which a radio halo and relic were discovered with the 74 MHz VLA (Kassim et al., 2001). Unfortunately, current low frequency telescopes lack the sensitivity to detect the great majority of radio clusters and relics which are thought to exist. It is estimated that with instruments such as LOFAR and the LWA, the relic and halo population may increase to hundreds or even thousands, including at higher red-shifts.

6 Bubbles in cooling flow clusters

A hypothesis to explain the *XMM-Newton* observed deficit of cool gas previously expected at the center of cooling flow clusters is illustrated by the 74 MHz radio emission (contours) overlay on the *Chandra* X-ray image of the Perseus cluster in Fig. 8. A current theory is that radio sources at the center of clusters inflate bubbles of relativistic particles that buoyantly rise through the hot X-ray cluster gas. This could explain the morphology of the observed radio and X-ray emission, and there are implications for the heating of the intracluster gas and the transport of magnetic fields

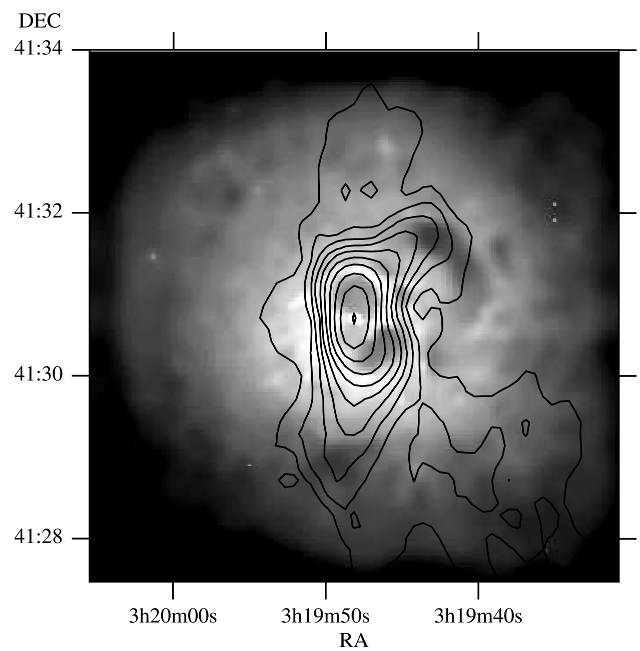

Figure 8: Overlay of steep spectrum 74 MHz radio emission (contours) on *Chandra* X-ray image of Per A from Fabian et al. (2002).

from the central active galactic nucleus (AGN) to the

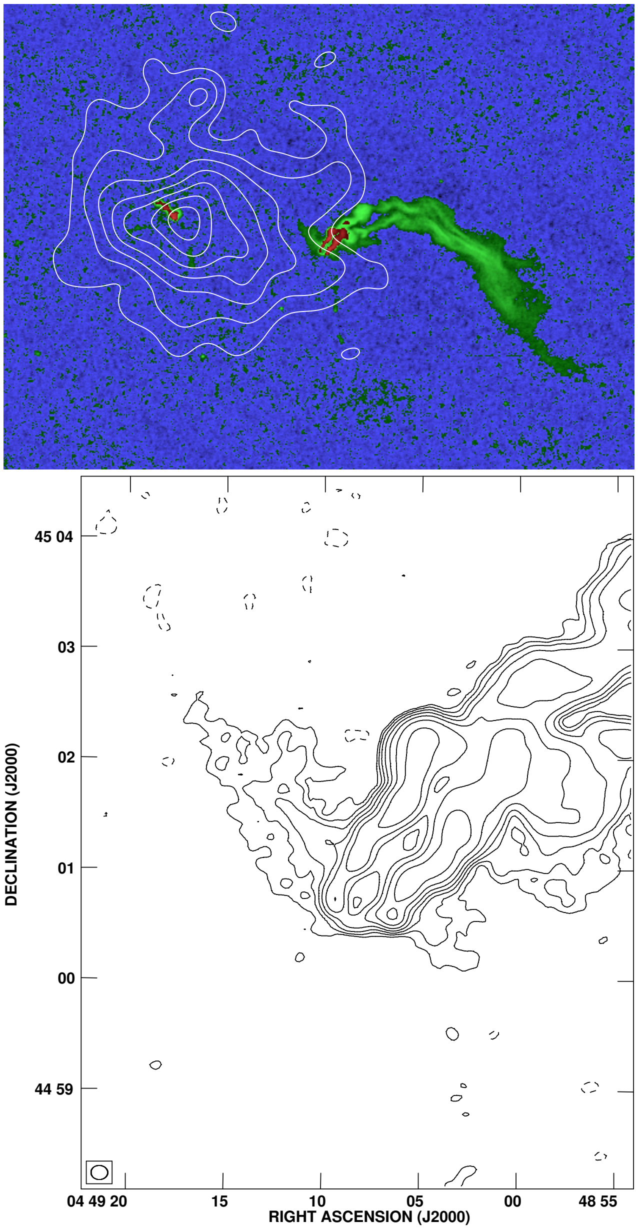

Figure 9: (a) *ROSAT* X-ray (contours) overlay on 330 MHz VLA radio (color) image of the field containing 3C129 (large radio galaxy) and 3C129.1 (small diameter source near the peak of the X-ray emission). (b) Blow up of 330 MHz radio emission near the head of 3C129, showing the presumed relic or fossil radio plasma source. Contour levels are 1.95 mJy beam^{-1} × (−2, −1, 1, 2, 4, 8, 16, 32, 64).

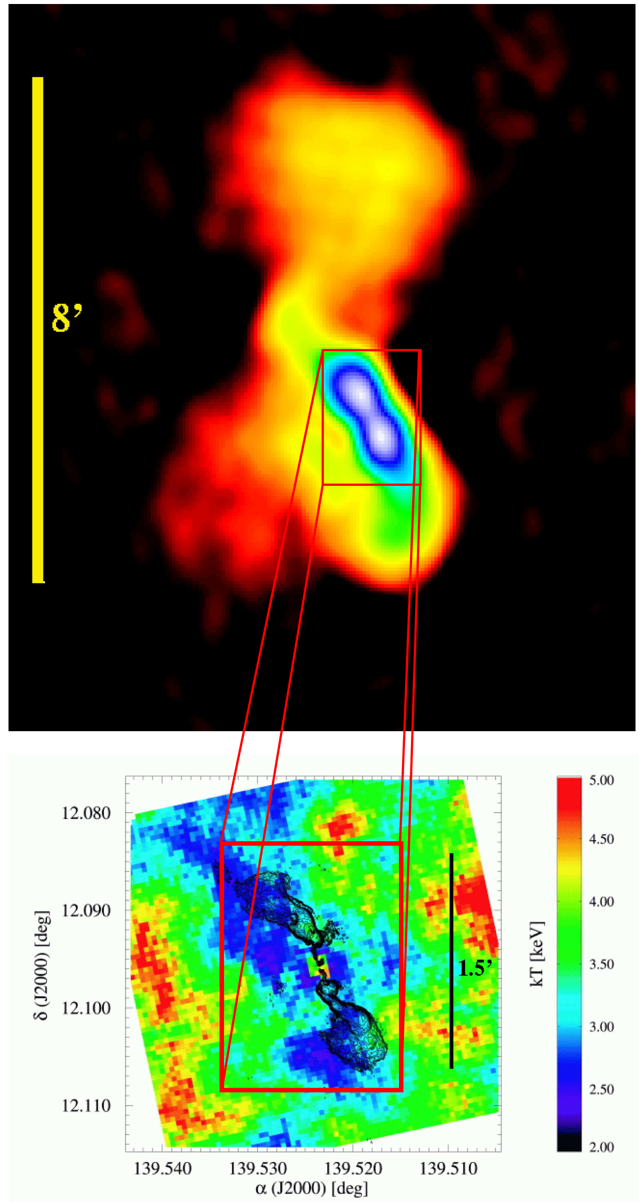

Figure 10: (a) (Top) 74 MHz radio image of Hydra A; (b) (Bottom) 6 cm VLA radio (contours overlaid on *Chandra* X-rays in color). Note that the full extent of the radio emission is revealed only on the 74 MHz image (Lane et al., 2004a, 2005).

outer regions of clusters—where they are observed. In Fig. 9 an outer and presumably older bubble seen in the X-ray image (grey-scale) is revealed to contain relativistic electrons via the steep spectrum 74 MHz spur (contours) extending toward its location (Fabian et al., 2002).

7 Detecting re-energized fossil radio plasma

Figure 9 shows the head-tail radio galaxy 3C129 "plunging" toward the center of the X-ray emitting cluster in which it resides (Lane et al., 2002). Near the head of the radio galaxy a very steep spectrum feature ($\alpha \approx -2$) that might represent fossil radio plasma that is now being re-energized by the interaction. Observations at 74 MHz with the VLA+PT link have been recently obtained in order to provide a better constraint on its spectrum. If steep spectrum features such as this are common they would have been missed by past observations but would be detected in great numbers by the LWA and LOFAR.

8 What is the real size of radio galaxies?

Because of limits in surface brightness sensitivity of interferometers to extended non-thermal radio emission, the true size of radio galaxies may often be revealed only in low frequency radio maps. The 74 MHz image of Hydra A in Fig. 10 shows how much larger the source is than as revealed in previous higher frequency images (Lane et al., 2004a, 2005). Figure 10 also shows an X-ray overlay, but limited only to the center of the source. Past underestimation of the full source extent had limited the focus of X-ray studies to the central region.

9 Summary

In this paper we have shown unique new high resolution, long wavelength images that can be used to study a variety of important physical processes in non-thermal sources. They can also provide unique information on the interaction between thermal and non-thermal sources as tracers of thermal absorption. All these observations provide an excellent compliment to both higher frequency radio observations as well as X-ray observations.

The examples provided in this paper illustrate a wide variety of astrophysical scenarios several of which were explored in greater depth by focused presentations elsewhere in this meeting. In review, the following summarizes the key scientific applications of long wavelength radio observations as presented here and in related talks in these proceedings:

- Shock acceleration via the radio spectrum (SNRs, radio galaxies, clusters);
- SNe ejecta via internal thermal absorption (SNRs);
- SNR-molecular cloud collisions via local thermal absorption (SNRs/star forming regions);
- Ionized gas in the ISM via line of sight thermal absorption (ISM);
- Re-acceleration of fossil electron populations via steep spectrum radio emission (clusters and relics);
- Delineating the full size of radio sources (SNRs, radio galaxies, clusters);
- Self-absorption processes via the radio spectrum (hot spots of radio galaxies); and
- Pressure balance between thermal and relativistic plasmas (via radio spectrum).

The renaissance in low frequency radio astronomy stimulated by the success of the 74 MHz system at the VLA continues to grow. It foreshadows the opening of a new window on one of the most unexplored regions of the electromagnetic spectrum below 100 MHz by both the Low Frequency Array (LOFAR) and the Long Wavelength Array (LWA). Each of these instruments will surpass the power of previous long wavelength imaging systems, including the pioneering 74 MHz VLA system, by at least two orders of magnitude. Consequently the potential for new discoveries outside the broad range of physical processes considered in this paper is significant.

Acknowledgments

Basic research in radio astronomy at the NRL is supported by the Office of Naval Research. The National Radio Astronomy Observatory is a facility of the National Science Foundation operated under cooperative agreement by Associated Universities, Inc. Delaney et al. Cas A work is supported by Smithsonian grant SMITHSONIAN/GO1-2051A/NASA and NASA grant HST-AR-09537-01 at the University of Minnesota.

References

Brogan, C. L., Dyer, K. K., Kassim, N. E., Lazio, T. J., Lacey, C. K. 2002, Bull. Amer. Astron. Soc., 200, 1504

Chen, Y., Slane, P. O. 2001, ApJ, 563, 202

Clarke, T. E., Kassim. N., Ensslin, T., Neumann, D. 2003, 25th Meeting of the IAU, Joint Discussion 10

Delaney, T., et al. 2005, in *X-Ray and Radio Connections*, eds. Sjouwerman, L.O. & Dyer, K.K., http://www.aoc.nrao.edu/events/xraydio

Fabian, A. C., Celotti, A., Blundell, K. M., Kassim, N. E., Perley, R. A. 2002, MNRAS, 331, 369

Frail, D. A., Goss, W. M., Reynoso, E. M., Giacani, E. B., Green, A. J., Otrupcek, R. 1996, AJ, 111, 1651

Gizani, N., Cohen, A. S., Kassim, N. E. 2004, MNRAS, submitted

Kassim, N. E., et al. 2004, ApJ, in preparation

Kassim, N. E., Clarke, T. E., Ensslin, T. A., Cohen, A. S., Neumann, D. M. 2001, ApJ, 559, 785

Kassim, N. E., Perley, R. A., Carilli, C. L., Harris, D. E., Erickson, W. C. 1996, in Cygnus A - Study of a Radio Galaxy, eds. Carilli, C. L. & Harris, D. E. (Cambridge: Cambridge University Press) p. 182

Lane, W. M., Clarke, T. E., Taylor, G. B., Perley, R. A., Kassim, N. E. 2004a, AJ, 127, 48

Lane, W. M., et al. 2005, in *X-Ray and Radio Connections*, eds. Sjouwerman, L.O. & Dyer, K.K., http://www.aoc.nrao.edu/events/xraydio

Lane, W. M., Kassim, N. E., Ensslin, T. A., Harris, D. E., Perley, R. A. 2002, AJ, 123, 2985

Reach, W. T., Rho, J. 1999, ApJ, 511, 836

Reach, W. T., Rho, J., Jarrett, T. H., Lagage, P. 2002, ApJ, 564, 302