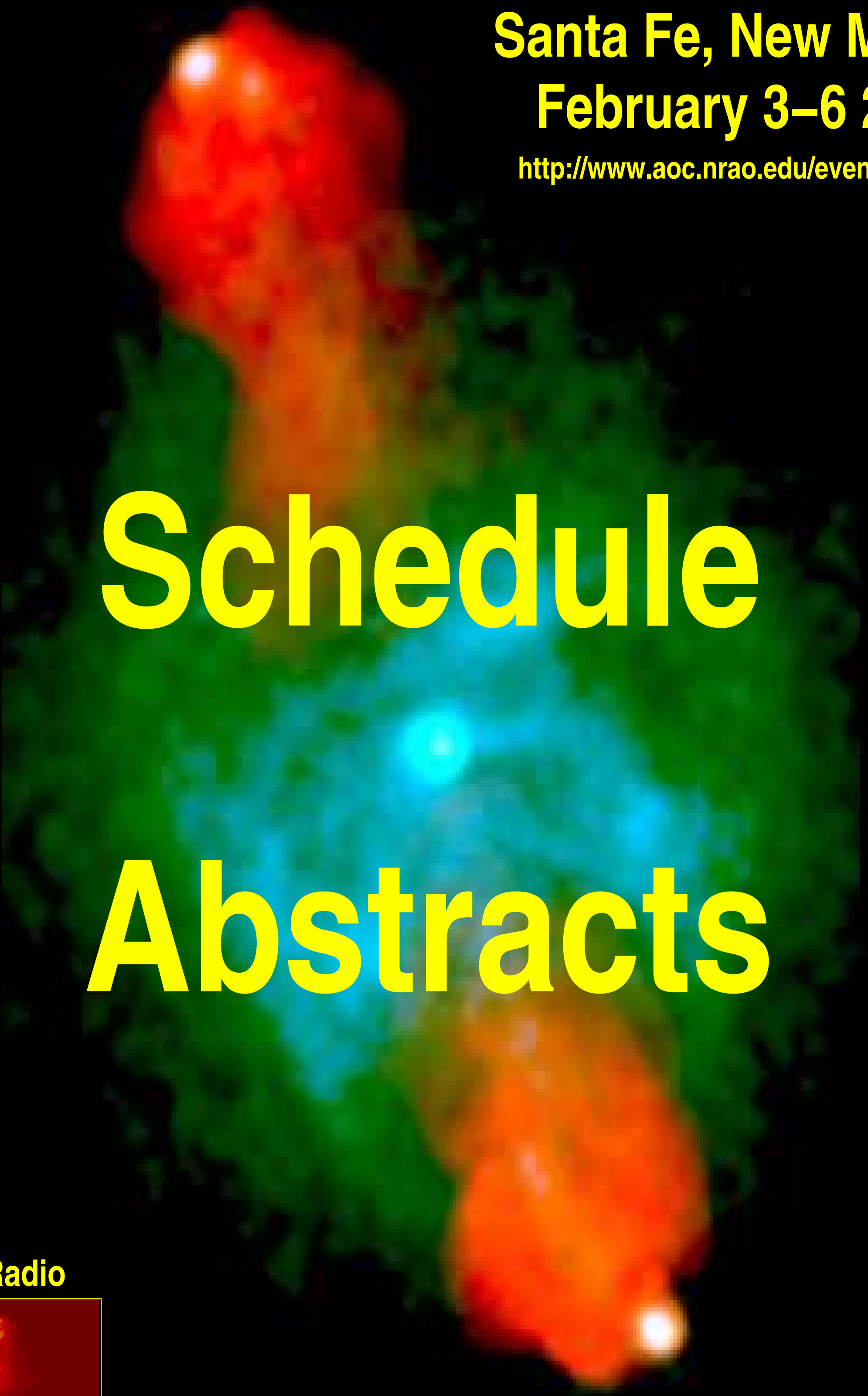
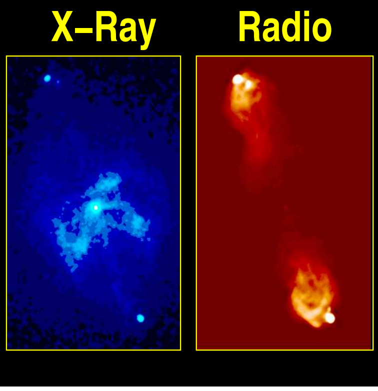
# X–Ray and Radio Connections

Santa Fe, New Mexico
February 3–6 2004
http://www.aoc.nrao.edu/events/xraydio



# Schedule

# Abstracts



# X-Ray and Radio Connections
# Tuesday Schedule

## 3 February, morning program:

**07:30 Registration, COFFEE & TEA, Posters**

### 1. Introduction and Particle Acceleration

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|---|---|---|
| **08:15** | *Welcome and announcements* | Kristy Dyer and Loránt Sjouwerman |
| **08:30** | *Particle acceleration* | John Kirk |

### 2. Colliding Stellar Winds

| | | |
|---|---|---|
| **09:30** | *The theory of colliding stellar winds* | Julian Pittard |
| **10:05** | *Multi-wavelength observations of colliding stellar winds* | Michael Corcoran |

**BREAK**

| | | |
|---|---|---|
| **11:15** | *Probing the structure of colliding wind binaries with high-resolution X-ray spectra* | David Henley |
| **11:35** | *Poster presentations and discussion: Colliding Stellar Winds* | |

**12:00 – 14:00 LUNCH**

## 3 February, afternoon program:

### 3. Massive Star Cluster Outflows

| | | |
|---|---|---|
| **14:00** | *The yin and yang of X-ray/radio diagnostics of colliding flows* | Ken Gayley |
| **14:35** | *Outflows and jets from massive star-forming clusters* | Henrik Beuther |
| **14:55** | *Winds driven by massive star clusters* | Sergiy Silich |

**BREAK**

| | | |
|---|---|---|
| **15:45** | *Parsec-scale X-ray flows in high-mass star-forming regions* | Leisa Townsley |
| **16:05** | *The interstellar environment near the Galactic center Arches cluster* | Cornelia Lang |
| **16:25** | *Poster presentations and discussion: Massive Star Cluster Outflows* | |
| **16:45** | *Poster session* | |

**17:30 – 19:30 MARGARITA FIESTA**

# X-Ray and Radio Connections
# Wednesday Schedule

## 4 February, morning program:

**07:30 Registration, COFFEE & TEA, Posters**

### 4. Supernova Remnants

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|---|---|---|
| **08:30** | *Dynamics and nonthermal emission of supernova remnants* | Steve Reynolds |
| **09:05** | *Observations of supernova remnants* | Anne Decourchelle |
| **09:45** | *Hydrodynamic simulations of supernova remnants including particle acceleration* | Don Ellison |
| **10:05** | *X-ray and radio morphologies of LMC supernova remnants* | John Dickel |

**BREAK**

| | | |
|---|---|---|
| **10:55** | *X-ray and radio (and optical) observations of Cas A* | Tracey DeLaney |
| **11:15** | *Monitoring X-ray emission from SN1986J* | John Houck |
| **11:35** | *Poster presentations and discussion: Supernova Remnants* | |

**12:10 – 14:00 LUNCH**

## 4 February, afternoon program:

### 5. Pulsar Wind Nebulae

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|---|---|---|
| **14:00** | *Multiwavelength studies of pulsar wind nebulae* | Andrew Melatos |
| **14:35** | *Pulsar wind nebulae* | Yuri Lyubarski |

**BREAK**

| | | |
|---|---|---|
| **15:45** | *Pulsar parallaxes, bow shock nebulae and the interstellar medium* | Shami Chatterjee |
| **16:05** | *Poster presentations and discussion: Pulsar Wind Nebulae* | |
| **16:30** | *Poster session* | |

**17:30 – 18:30 COCKTAILS**

# X-Ray and Radio Connections
# Thursday Schedule

## 5 February, morning program:

**07:30 Registration, COFFEE & TEA, Posters**

### 6. X-Ray and Radio Observations

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|---|---|---|
| **08:30** | *Mining the X-ray archives at the HEASARC: a users guide* | Stephen Drake |
| **09:05** | *Mining radio archives* | Michael Rupen |
| **09:45** | *Preparing a competitive radio proposal* | Ed Fomalont |
| **10:05** | *How to write a good proposal for X-ray observations* | Fred Seward |

**BREAK**

### 7. Dissipation of Jets

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|---|---|---|
| **10:55** | *Theory of jet dissipation* | Dave De Young |
| **11:30** | *Observations of jet dissipation* | Robert Laing |

**12:10 – 14:00 LUNCH**

## 5 February, afternoon program:

| | | |
|---|---|---|
| **14:00** | *Jet dissipation and particle acceleration* | Martin Hardcastle |
| **14:20** | *Radio jets in cooling cores* | Jean Eilek |
| **14:40** | *Combined synthetic X-ray and radio observations of simulated radio jets* | Ian Tregillis |
| **15:00** | *Jet/environment interactions of FR-I and FR-II radio galaxies* | Judith Croston |
| **15:20** | *Poster presentations I: Dissipation of Jets* | |

**BREAK**

| | | |
|---|---|---|
| **16:05** | *Interaction of jets with inhomogeneous interstellar media* | Geoff Bicknell |
| **16:25** | *The radio/X-ray connection in Abell 2029* | Tracy Clarke |
| **16:45** | *The jet/ISM interaction in three nearby radio galaxies as seen with Chandra* | Ralph Kraft |
| **17:05** | *Poster presentations II and discussion: Dissipation of Jets* | |

**18:00 – 19:00 COCKTAILS**

# X-Ray and Radio Connections
# Friday Schedule

## 6 February, morning program:

**07:30 Registration, COFFEE & TEA, Posters**

### 8. Cluster Mergers

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|---|---|---|
| **08:30** | *Mergers and non-thermal processes in clusters of galaxies* | Craig Sarazin |
| **09:05** | *Observations of cluster mergers* | Luigina Feretti |
| **09:45** | *Energy balance in clusters of galaxies* | Patrick Motl |
| **10:05** | *Heating of the ICM due to mixing of fossil plasma* | Matthias Hoeft |
| **10:25** | *Poster presentations: Cluster Mergers* | |

**BREAK**

| | | |
|---|---|---|
| **11:10** | *The Sunyaev-Zeldovich effect in nearby massive clusters as observed by the CBI* | Steven Myers |
| **11:30** | *Chandra temperature maps for galaxy clusters with radio halos* | Maxim Markevitch |
| **11:50** | *Computer simulations of nonthermal particle and photon spectra from merging clusters of galaxies* | Robert Berrington |
| **12:10** | *Discussion: Cluster Mergers* | |

**12:30** *Meeting summary*

## 6 February, afternoon program:

**13:00 LUNCH BANQUET**

# Schedule and Abstracts

# Session 1

# Particle Acceleration

## 1.1 Particle acceleration

*J. G. Kirk*

**Abstract:**

In astrophysical objects, particles can be accelerated either by tapping into kinetic energy (e.g., at shocks) or by dissipating magnetic energy (e.g., by reconnection) or wave energy (e.g., by the second order Fermi process). Although different in detail, there are strong similarities in the models used to describe these processes. In this review I will try not only to emphasize these similarities, but also to stress the important differences which arise between the mechanisms when they operate in highly relativistic and in nonrelativistic environments.

**Notes:**

Submitted by John Kirk [john.kirk@mpi-hd.mpg.de]

## Session 2

# Colliding Stellar Winds

## 2.1 The theory of colliding stellar winds

*J.M. Pittard*

### Abstract:

The collision of the hypersonic winds in early-type binaries produces shock heated gas, which radiates thermal X-ray emission, and relativistic electrons, which emit non-thermal radio emission. In this review I present our current understanding of the emission in these spectral regions and discuss models which have been developed for the interpretation of this emission. Throughout I highlight processes which affect the resulting emission and conclude with ideas for future research.

### Notes:

## 2.2 Multi-wavelength observations of colliding stellar winds

*Mike Corcoran*

### Abstract:

Wind-wind collisions produce radiation throughout the electromagnetic spectrum. Colliding wind emission provides important information on stellar and wind parameters, and can be especially useful for understanding short-lived, extremely massive stars which may be hard to study by more conventional methods. But detection of colliding wind emission depends on a number of physical and geometrical circumstances and can be challenging in many cases. This review will discuss new observations of colliding wind systems and illustrate how the detection (or non-detection) of colliding wind emission can help determine the physical properties of massive stellar systems.

### Notes:

Submitted by Michael Corcoran [corcoran@barnegat.gsfc.nasa.gov]

## 2.3 Probing the structure of colliding wind binaries with high-resolution X-ray spectra

*David Henley, Ian Stevens and Julian Pittard*

### Abstract:

Insights into the structure of colliding winds can come from the radio and the X-ray. In both cases, the observed flux and spectrum vary throughout the orbit, largely due to the changing column density to the wind-wind collision region. High-resolution X-ray spectra enable us to probe in detail the dynamics and structure of the wind-wind collision region, and can give us information on the shape, orientation and velocity structure of the wind-wind collision, as well is its temperature and density structure. We present recent calculations of X-ray line profiles from colliding wind binaries. We have applied this model to systems such as Gamma Velorum, WR 140 and Eta Carinae. The implications of this work and of related radio observations on our understanding of colliding winds will be discussed.

### Notes:

## 2.4 On the X-ray emission from the radio source Sgr A*

*Robert Coker (LANL) and Julian Pittard (University of Leeds, UK)*

### Abstract:

Recent infrared observations of the Galactic Center have permitted the estimation of orbital parameters for the eight O stars closest to the compact, nonthermal radio source, Sgr A*. The emission of Sgr A* is thought to be due to the accretion of gas down the potential well of a $2-3\times10^{6}$ solar mass black hole at the dynamical heart of the Milky Way. The O stars are located within 0.03 pc of Sgr A* and are likely to have significant stellar winds. Since they are deep within the potential well of a black hole, much of their winds are gravitationally bound. These hot winds may be piling up and emitting significantly in the X-rays. Thus it is possible that the emission from the recently detected compact Chandra source may at least in part be due to the winds of these O stars rather than the hot gas close to the event horizon of the black hole. This has serious implications for applicable black hole accretion models. From preliminary 3D numerical simulations which treat the 8 O stars as mass sources moving on individual orbits, we have constructed simulated X-ray images. We present these images and discuss their impact on accretion models for Sgr A*.

### Notes:

Submitted by Robert Coker [robc@lanl.gov]

## Session 3

# Massive Star Cluster Outflows

## 3.1 The yin and yang of X-ray/radio diagnostics of colliding flows

*Kenneth Gayley*

### Abstract:

Many astrophysical concepts appear clearer when seen in relief against seemingly opposite limits, especially when similarities underlie the obvious differences. This idea would seem to be a key motivator for a conference covering opposite ends of the electromagnetic spectrum, and indeed there are many processes that appear in the generation of both X-rays and radio during the collision of supersonic flows that are best considered in opposing limits. This review talk will concentrate on a few such contrasts, including the nature of thermal vs. nonthermal emission from energy conserving vs. momentum conserving interactions, for smooth vs. clumpy flows that are adiabatic vs. highly radiative. Special attention to colliding winds will be included in with the more general concepts.

### Notes:

Submitted by Kenneth Gayley [kenneth-gayley@uiowa.edu]

## 3.2 Outflows and jets from massive star-forming clusters

*H. Beuther*

**Abstract:**

This talk will review observations toward outflows and jets of young massive star-forming regions from radio to X-ray wavelength. The presentation will tackle questions regarding, e.g., driving mechanisms, energetics, multiplicities and feedback processes to the interstellar medium. Finally, open questions and possible observational approaches will be discussed.

**Notes:**

Submitted by Henrik Beuther [hbeuther@cfa.harvard.edu]

## 3.3 Winds driven by massive star clusters

*Silich, S., Tenorio-Tagle, G. & Rodriguez-Gonzalez, A.*

**Abstract:**

In the original stationary solution for spherically symmetric winds proposed by Chevalier and Clegg (1985) as well as in a number of more recent numerical calculations the outflows were assumed to be adiabatic. Here I present a self-consistent semi-analytical model of stationary winds driven by massive young stellar clusters taking radiative cooling into account and show that radiative cooling may result in the establishment of a temperature distribution radically different from that predicted by the adiabatic solution. Radiative outflows intrinsic properties and their appearance in the X-ray and visible line regimes are thoroughly discussed.

**Notes:**

Submitted by Sergiy Silich [silich@inaoep.mx]

## 3.4 Parsec-scale X-ray flows in high-mass star-forming regions

*L. Townsley, E. Feigelson, T. Montmerle, P. Broos, Y.-H. Chu, G. Garmire, and K. Getman*

### Abstract:

We present Chandra/ACIS images of several high-mass star forming regions. The massive stellar clusters powering these H II regions are resolved at the arcsecond level into hundreds of stellar sources, similar to those seen in closer young stellar clusters. However, we also detect diffuse X-ray emission on parsec scales that is spatially and spectrally distinct from the point source population. For nearby regions (e.g. M 17 and Rosette) the emission is soft, with plasma temperatures less than 10 million degrees, in contrast to what is seen in more distant complexes (e.g. RCW 49, W 51). This extended emission most likely arises from the fast O-star winds thermalized either by wind-wind collisions or by a termination shock against the surrounding media. We establish that only a small portion of the wind energy and mass appears in the observed diffuse X-ray plasma; in the blister H II regions, we suspect that most of it flows without cooling into the low-density interstellar medium through blow-outs or fissures in the surrounding neutral material. These data provide compelling observational evidence that strong wind shocks are present in H II regions.

### Notes:

Submitted by Leisa Townsley [townsley@astro.psu.edu]

## 3.5 The interstellar environment near the Galactic center Arches cluster

*C. C. Lang*

### Abstract:

The understanding of the unique Galactic Center Radio Arc region (located $\sim$30 pc in projection from Sgr A*) has changed dramatically over the last 10 years with the advent of high-resolution near-infrared and X-ray observations. The unusually-shaped thermal radio filaments are now understood to be ionized by two luminous clusters which each contain more than 100 young, massive stars. I will review the environment near the Arches cluster - the complex interplay between these massive stars, their powerful stellar winds, and the surrounding ionized, atomic and molecular interstellar media. The combination of radio and X-ray observations in particular provides crucial insight as to the nature of stellar-interstellar interactions in this extreme region of the Galaxy.

### Notes:

Submitted by Cornelia Lang [cornelia-lang@uiowa.edu]

## 3.6 X-ray and radio emission from two Galactic center star forming regions: Sgr B and Sgr C

*Casey Law and Farhad Yusef-Zadeh*

### Abstract:

Molecular line observations have shown Sgr B (G0.6−0.1) to be one of the most spectacular star forming regions in Galaxy. Similarly, Sgr C (G359.4−0.1) is host to sites of star formation as well as a collection of unusual nonthermal radio filaments. Using Chandra, Very Large Array, and Swedish-ESO Submillimetre Telescope observations, we study the correlations between radio continuum, CS(2–1) molecular line, and X-ray emission from these sources, with a focus on the distribution of the neutral iron 6.4 keV line emission. We examine the hypothesis that such emission is evidence of past flaring from Sgr A*. We also study the distribution of X-ray and radio point sources throughout these regions.

### Notes:

Submitted by Casey Law [claw@northwestern.edu]

# Session 4

# Supernova Remnants

## 4.1 Dynamics and nonthermal emission of supernova remnants

*Stephen P. Reynolds*

### Abstract:

Supernova remnants illustrate the return of mass and energy from stars to the interstellar medium, connecting one generation of star formation with the next. Recent advances in radio and X-ray observational capabilities allow the study of remnants to cast light on these processes. In addition, such studies can be important in understanding the progenitors of Type Ia supernovae, and the core-collapse supernovae apparently associated with $\gamma$-ray bursts. I shall review briefly some advances in studies of the dynamics of supernova remnants, with an emphasis on multidimensional simulations, and the implications for radio and X-ray observations. I shall then describe the applications of shock acceleration theory in the context of remnants, focusing on synchrotron emission from radio through X-ray bands, and what it can tell us about the nature of remnants and the physics of particle acceleration.

### Notes:

Submitted by Stephen Reynolds [steve_reynolds@ncsu.edu]

## 4.2 Observations of supernova remnants

*Decourchelle, Anne*

### Abstract:

Shocks in supernova remnants (SNRs) are long thought to be responsible for the acceleration of Galactic Cosmic Rays up to the knee ($>$ 1000 TeV). Synchrotron radio emission attests to the presence of GeV accelerated electrons. With the advent of X-ray spectro-imagery, observational evidence has been obtained for the acceleration of electrons up to energies of about 100 TeV. I will review the recent observations of nonthermal emission in young ejecta-dominated SNRs and in synchrotron-dominated SNRs like SN 1006 and G347.3−0.5. I will illustrate the importance of combining X-ray and radio data for characterizing the synchrotron emission and its spectral variations, as well as for studying the interaction of the blast wave with the ambient medium. These results are crucial for the understanding of particle acceleration in SNRs and the origin of the Galactic Cosmic-Rays. They uniquely provide constraints on poorly known aspects of particle acceleration like the magnetic turbulence, the acceleration efficiency and potentially the level of particle injection.

### Notes:

Submitted by Anne Decourchelle [adecourchelle@cea.fr]

## 4.3 Hydrodynamic simulations of supernova remnants including particle acceleration

*Don Ellison, Anne Decourchelle, and Jean Ballet*

### Abstract:

A number of supernova remnants (SNRs) show nonthermal X-rays assumed to be synchrotron emission from shock accelerated TeV electrons. If the shock acceleration process in SNRs is efficient and nonlinear, as is likely, the existence of these TeV electrons has important implications for the production of galactic cosmic rays, for the SNR evolution, and for the interpretation broad-band photon emission from radio to $\gamma$-rays. We report on a technique which couples nonlinear shock acceleration with a hydrodynamic simulation of SNR evolution. The model includes the backreaction of the accelerated particles on the structure of the forward and reverse shocks, and the production of photons from the shock-heated gas and accelerated particle populations.

### Notes:

Submitted by Don Ellison [don_ellison@ncsu.edu]

## 4.4 X-ray and radio morphologies of LMC supernova remnants

*John R. Dickel*

### Abstract:

The large Magellanic Cloud provides an invaluable sample of supernova remnants for comparative X-ray and radio morphological studies. It contains a good variety of remnants all at the same distance. There are pulsar wind nebulae (with and without observable pulsars) with non-thermal radio and X-ray synchrotron emission, shell SNRs with thermal X-rays and non-thermal radio emission, and composite objects containing both of these components. There are also mixed-morphology SNRs with shell radio emission and internal thermal X-rays. Often the X-ray and radio emission match well but sometimes they are surprisingly different in structure for reasons that are still being investigated.

### Notes:

Submitted by John Dickel [johnd@astro.uiuc.edu]

## 4.5 X-ray and radio (and optical) observations of Cas A

*T. DeLaney, L. Rudnick, R. Fesen, U. Hwang, T. W. Jones, R. Petre, & J. Morse*

**Abstract:**

We have performed a multiwavelength comparison of Cassiopeia A using Very Large Array, Hubble Space Telescope, and Chandra images. By separating components spectrally, we find clear associations between the emission at the three wavebands. We separate the emitting material into two components - shocked circumstellar medium and shocked ejecta, which show the same respective morphologies and proper motions in the different bands. In the shocked circumstellar medium, we find matched low-energy-enhanced X-ray emission and optical quasi-stationary flocculi, and X-ray continuum-dominated emission matched with filamentary radio structures. In the ejecta, we find matched X-ray and optical O, Si, and S line emission and flat-spectrum radio emission.

**Notes:**

Submitted by Tracey DeLaney [tdelaney@astro.umn.edu]

## 4.6 Monitoring X-ray emission from SN1986J

*Houck, John C. (MIT)*

### Abstract:

SN1986J ranks as one of the most luminous, X-ray bright supernovae ever observed. The X-ray emission is attributed to circumstellar interaction with the dense wind from its red supergiant progenitor star. Because X-ray bright supernovae are rare and relatively faint, only a small number have been observed in X-rays at an age of more than a year or two. I present results from recent Chandra observations of SN1986J which, combined with earlier ASCA and Rosat/PSPC data, yield an X-ray light curve spanning much of the first 20 years of the supernova's evolution. Combined with observations in other wave bands, these data provide strong constraints on models for this type IIn supernova.

### Notes:

Submitted by John Houck [houck@space.mit.edu]

## 4.7 Evidence of a curved cosmic-ray electron spectrum in the supernova remnant SN1006

*G. E. Allen, J. C. Houck, and S. J. Sturner*

### Abstract:

We present *Chandra* ACIS data for the eastern rim of the supernova remnant SN 1006. A joint spectral analysis of this X-ray data, some radio data and the CANGAROO $\gamma$-ray data was performed using a model that includes synchrotron radiation and inverse-Compton scattering of the cosmic microwave background. The nonthermal electron spectrum used to compute the emission spectra for these two components is the traditional exponentially cut-off power law with one notable difference. The power-law index is a linear function of the logarithm of the momentum, not just a constant. Inclusion of the linear term enables us to show, for the first time, that the electron spectrum of SN 1006 seems to flatten with increasing energy. At 1 GeV (i.e. radio–synchrotron-emitting energies), the power-law index is about 2.2. At 30 TeV (i.e. X-ray–synchrotron-emitting energies), the index is about 2.0. This result is qualitatively consistent with theoretical models and implies that cosmic rays are dynamically important, not "test" particles. The joint spectral analyses also enable us to independently fit the values of the "maximum" energy of the electrons and the total strength of the downstream magnetic field. Confidence contour maps for these two parameters are presented.

### Notes:

Submitted by Glenn Allen [gea@space.mit.edu]

## 4.8 The interpretation of multiwavelength spectra in SNR RX J1713.7−3946

*Matthew G. Baring*

### Abstract:

The recent CANGAROO detection of TeV $\gamma$-rays from the southern hemisphere remnant RX J1713.7−3946 has spawned a debate over whether this data provides evidence for the production of cosmic ray ions in this remnant. Published work has argued against an inverse-Compton origin for these photons from a population of electrons that generates radio to X-ray synchrotron emission. Such conclusions were predicated on a test-particle (linear) model for shock acceleration. Non-linear models of acceleration are widely regarded as appropriate for remnant shells, and generate multiwavelength spectra that can differ significantly from test-particle predictions. This paper explores such non-linear models and their impact on the expectations for radio/X-ray synchrotron spectra, and inverse-Compton $\gamma$-ray spectra. It is found that reasonable values of environmental parameters such as density and magnetic field strength can yield acceptable fits to the radio, X-ray, and TeV fluxes and spectra, and can accommodate the constraining bounds imposed by a proximate unidentified EGRET source.

### Notes:

Submitted by Matthew Baring [baring@rice.edu]

## 4.9 Finding the missing remnants: a low frequency survey of the Galactic plane from $l$=+5 to +20°

*C.L. Brogan, Y. Gelfand, B.M. Gaensler, N. E. Kassim, & T. J. Lazio*

### Abstract:

Predictions of the Galactic supernova remnant (SNR) rate and statistical studies of the current Galactic supernova remnant census both indicate that there should be many more SNRs in our Galaxy than are currently known ($\sim$ 230). This paucity of SNRs is likely due in part to selection effects, which are most severe toward the inner Galaxy where the diffuse nonthermal Galactic plane emission coupled with the thermal emission from HII regions causes the most confusion. We present a high-resolution, high dynamic range survey of the Galactic plane from $\ell = +5$ to $+20°$ ($b = -1.5$ to $1.5°$) using 330 MHz observations with the Very Large Array (VLA). At this frequency we exploit the nonthermal spectra of SNRs while our high angular resolution allows us to separate them from the diffuse Galactic emission. We present a number of newly discovered SNRs from the initial stages of the survey, together with supporting evidence from archival X-ray, IR, and radio data. The National Radio Astronomy Observatory is a facility of the National Science Foundation operated under cooperative agreement by Associated Universities Inc. Basic research in radio astronomy at the Naval Research Laboratory is supported by the Office of Naval Research.

### Notes:

Submitted by Crystal Brogan [cbrogan@ifa.hawaii.edu]

## 4.10 Radio identification of SNR and PWNe candidates in M31

*Yosi Gelfand, Joe Lazio, and Bryan Gaensler*

**Abstract:**

By comparing the sourcelist produced by a four hour 90cm (325 MHz) observation of M31 with other radio, optical, and X-ray surveys of the region, we have identified five supernova remnants candidates (SNR) and three pulsar wind nebulae (PWN) candidates. The radio properties of the five SNR candidates are very similar to known SNRs in the Milky Way, while two of the three PWN candidates are brighter than the Crab Nebula, but have X-ray luminosities similar to that of Milky Way PWN.

**Notes:**

Submitted by Joseph Gelfand [jgelfand@cfa.harvard.edu]

## 4.11 A multiwavelength study of the mixed-morphology supernova remnant W28

*Jonathan W. Keohane, Jeonghee Rho, Thomas G. Pannuti, Kazimierz J. Borkowski and P. Frank Winkler*

### Abstract:

We present Chandra and ROSAT HRI X-ray observations and new optical images of the mixed-morphology supernova remnant W28, which we compare with Very Large Array and ROSAT PSPC data from the literature. A high resolution ROSAT HRI mosaicked image reveals a globally center-filled X-ray emission as seen in the PSPC images, but HRI image shows a few sharp filament structures in the north where the molecular cloud interacting with clouds, and the northeastern shell is broken into a few clumps, instead of a smooth shell as seen in the optical. Our Chandra image details the shape and extent of the central emission, revealing a bright knotty region of about 5-10 arcminute in size. Our KPNO Schmidt images show complex filamentary structure, with a relative enhancement of [SII] compared to H$\alpha$ in the regions of known shock/cloud interactions and a relative enhancement of H$\alpha$ emission in the central X-ray emitting region. The Chandra spectra show no dominant difference between the center and the southwest shell source emission, which is in contrast with the prior ASCA observation because of confusion with a hard point source coincident with the southwestern shell. The central spectrum is dominated by line emission, confirming the thermal nature of central emission in mixed morphology remnants. Strong K$\alpha$ lines of Si and S are particularly prominent. Lower than expected line energies suggest the presence of low ionization stages of these elements in X-ray emitting gas. We will discuss possible explanations for this unexpected discovery and its implications for our understanding of mixed-morphology remnants.

### Notes:

Submitted by Jonathan Keohane [keohane@ipac.caltech.edu]

## 4.12 Preliminary radio analysis from X-ray/radio survey of nearby spiral galaxies

*L.A. Maddox(U. of Oklahoma), C.J. Stockdale(Marquette U.), J.J. Cowan(U. of Oklahoma)*

### Abstract:

We present new VLA observations of nearby spiral galaxies M101 (6cm, 20cm), M51 (20cm) and NGC3184 (20cm). This project constitutes a small part of a larger VLA/*Chandra* survey of spirals. A new 6cm observation of M51 will be presented if data is available. Comparison of radio sources in each galaxy will be made with those in M83. Preliminary identification of radio sources will be discussed for M101 and (if 6cm is available) M51. X-ray analysis will presented in a later paper (in progress).

### Notes:

Submitted by Larry Maddox [maddox@nhn.ou.edu]

## 4.13 Molecular gas interacting with the TeV $\gamma$-ray SNR G347.3−0.5

*Yoshiaki Moriguchi, Yasuo Fukui, Keisuke Tamura, Yasunobu Uchiyama, Junko Hiraga, Tadayuki Takahashi*

### Abstract:

Supernova remnants are believed to be sites of cosmic-ray acceleration. In particular, interacting region of dense molecular clouds with supernova remnant is suggested to be a effective site of proton acceleration, which emits synchrotron dominant X-rays and TeV $\gamma$-rays. Dense molecular gas toward the TeV-$\gamma$/synchrotron X-ray SNR is a good predictor to verify the existence of cosmic-ray protons. We present new high-resolution mm-wave observations of molecular gas at 1 kpc distance interacting with the TeV $\gamma$-ray SNR G347.3−0.5. The clouds are clearly associated with the nonthermal X-ray shell and one of the molecular clumps coincides with X-ray/$\gamma$-ray peak, providing strong evidence for proton acceleration. We have estimated the total energy of accelerated protons to be about $10^{48}$ erg, which corresponds to an acceleration efficiency of about 0.001, posing an observational constraint on the proton acceleration.

### Notes:

Submitted by Yoshiaki Moriguchi [mori@a.phys.nagoya-u.ac.jp]

## 4.14 High angular resolution X-ray and radio observations of the Galactic supernova remnant G266.2−1.2 (RX J0852.0−4622)

*T.G. Pannuti (JPL/Caltech), G.E. Allen (MIT), M.D. Filipovic (University of Western Sydney/ATNF), M. Stupar (University of Western Sydney/Macquarie University), P.A. Jones (ATNF) and J.W. Keohane (JPL/Caltech)*

### Abstract:

G266.2−1.2 (RX J0852.0−4622) is a member of the emerging class of Galactic supernova remnants (SNRs) which feature X-ray spectra dominated by non-thermal emission. This X-ray emission is believed to be synchrotron radiation produced by cosmic-ray electrons accelerated to TeV energies along the expanding shock fronts of the SNRs: therefore, a thorough study of this emission offers a crucial opportunity to probe the cosmic-ray acceleration process by SNRs in some detail. We are conducting a joint analysis of high angular resolution X-ray (Chandra) and radio (ATCA, MOST and Parkes) observations of this SNR to model the properties of the synchrotron-emitting population of cosmic-ray electrons accelerated by this SNR. As part of this study, we are also measuring the maximum energy of cosmic-ray electrons accelerated by this SNR to determine if G266.2−1.2 is currently accelerating cosmic-ray particles to the well-known "knee"-energy of the observed cosmic-ray spectrum. Initial results and conclusions from this work will be presented. This work is support by NASA Contract Number NAS8-39073.

### Notes:

Submitted by Thomas Pannuti [tpannuti@ipac.caltech.edu]

## 4.15 ATCA and XMM-Newton study of supernova remnants in NGC300

*J. L. Payne, M. D. Filipovic, T. G. Pannuti, P. A. Jones, N. Duric, G. L. White and S. Carpano*

### Abstract:

We present a radio and X-ray study of supernova remnants(SNRs) and HII regions in the nearby Sculptor Group Sd galaxy NGC300, based on new ATCA observations at the wavelengths of 13 and 20 cm, XMM-Newton observations, newly-processed ROSAT (PSPC/HRI; (Read & Pietsch, 2001)) and VLA (20/6 cm) images of this galaxy. We have investigated the physical properties at the X-ray and radio wavelengths of the 28 optical SNRs found by Blair & Long (1997) and have expanded on the multi-wavelength work done by Pannuti et al. (2000) on this same galaxy. We report 18 SNRs and 6 SNR candidates in NGC300. Five of these 18 SNRs are associated with optical SNRs and three have X-ray counterparts. We also investigate their brightness-diameter relation and luminosity functions. Three background radio sources are confirmed and 12 other sources could represent additional background objects. Twenty two correlations with OB associations within NGC300 correspond to either HII regions or SNRs making them a good tracer of SNRs near star-forming regions. Additionally, two of our sources may (or not) correlate to potential globular clusters of NGC300 reported by Kim et al. (2002).

### Notes:

Submitted by Jeffrey Payne [snova4@msn.com]

## 4.16 The center of the Andromeda galaxy

*LO Sjouwerman (NRAO), AKH Kong (CfA), MR Garcia (CfA), JR Dickel (UIUC), BF Williams (CfA), KE Johnson (UWisc), FA Primini (CfA), WM Goss (NRAO)*

### Abstract:

We report on sensitive high-resolution surveys of the central part of the Andromeda galaxy (M31) with Chandra in X-rays (17'x17') and with the Very Large Array in the radio at 4.9 and 8.4 GHz (6'x6'). The combination of the data has revealed a number of coincident sources of which the most interesting are the extended X-ray and radio SNRs. Also, the presumed super-massive central black hole M31* shows short-term and long-term variability at both radio and X-ray wavelengths.

### Notes:

Submitted by Lorant Sjouwerman [lsjouwer@nrao.edu]

## 4.17 X-ray properties of radio sources in M31 fields: XMM-Newton observations

*S. Trudolyubov and W. Priedhorsky*

### Abstract:

We present the results of XMM-Newton observations of radio-emitting objects in M31 fields. More than thirty bright X-ray sources were found to coincide with SNR candidates in M31 and background radio sources. We discuss the results of X-ray spectral and timing analysis with respect to individual sources as well as in the view of source population studies.

### Notes:

Submitted by Sergey Trudolyubov [sergeyt@citrus.ucr.edu]

## 4.18 Seven candidates for supernova remnants emitting synchrotron X-rays and their radio properties

*Masaru Ueno, Bamba Aya, Katsuji Koyama (Kyoto University)*

### Abstract:

Synchrotron X-rays are strong evidence for existence of high energy electrons in shells of supernova remnants (SNRs) since the discovery of them from SN1006. Using the ASCA Galactic plane survey, we found seven candidates for shell-type SNRs emitting synchrotron X-rays. Follow-up observations with Chandra or XMM-Newton were made for three of the candidates, and three of the others were deeply observed with ASCA. As a result, for five candidates, hard and featureless X-ray spectra and diffuse structures and were confirmed. Those spectra could be fitted with power-law models with photon indices of about 1.8 and indicate their origin is synchrotron emission. We estimated the maximum energy of accelerated electrons from wide band spectra connecting radio and X-ray bands for the five SNRs. Adding these new candidates to the radio sigma-D relation by Case & Bhattacharya (1998), we found that they are located in a radio faint region. One possible explanation is that SNRs accelerating high energy electrons have weak magnetic field.

### Notes:

Submitted by Masaru Ueno [masaru@cr.scphys.kyoto-u.ac.jp]

## Session 5

# Pulsar Wind Nebulae

## 5.1 Multiwavelength studies of pulsar wind nebulae

*A. Melatos*

### Abstract:

A pulsar wind nebula (PWN) is a synchrotron-emitting bubble of magnetic field and relativistic leptons powered by a pulsar wind and confined by the external environment, e.g. a supernova remnant, the ram pressure of the ISM, or the material around a binary companion. Coordinated observations of PWN from radio to optical wavelengths can constrain the physics of pulsar winds, as well as their environmental conditions, in unique ways. Several examples of multiwavelength PWN experiments, past and future, are reviewed and tied to recent progress in the underlying theory of pulsar wind electrodynamics.
(i) Imaging of the subarcsecond wisps in PWN constrains the equatorial ion fraction and predicts $\gamma$-ray (and neutrino) emission from hadronic processes, e.g. in the eccentric binary PSR B1259−63.
(ii) Polarization of the wisps and polar jet constrains the magnetic field geometry as a function of latitude, testing the hypothesis of magnetic fragmentation and regeneration driven by the magnetohydrodynamic kink instability.
(iii) Energy transport and the sigma paradox. Is Poynting flux converted gradually to kinetic-energy flux as the wind expands, as in a steady-state linear accelerator, or is the conversion lossy, due to reconnection in a wave-like (striped) outflow?
(iv) Future high-resolution imaging and polarimetry will probe the wave-like nature of pulsar winds by looking for the signatures of synchro-Compton radiation and/or magnetic reconnection, as well as modifications of the acceleration physics in the wind termination shock.
(v) Modeling of the nested H$\alpha$ and radio/X-ray emission from PWN bow shocks constrains the mean density and clumpiness of the ISM, the wind energy flux as a function of latitude, and the Mach number of the shock.

### Notes:

Submitted by Andrew Melatos [a.melatos@physics.unimelb.edu.au]

## 5.2 Pulsar wind nebulae

*Yuri Lyubarsky*

### Abstract:

Young, rapidly rotating pulsars are surrounded by compact synchrotron nebulae, the Crab Nebula being the best studied and most known example. These nebulae are continuously pumped by electron-positron plasma and magnetic field emanating from the pulsar in the form of relativistic, magnetized wind. High-resolution images in X-ray and optical bands revealed a peculiar "jet-torus" structure in the inner parts of these nebulae. This discovery clearly indicates significant anisotropy of the pulsar wind, which has been ignored so far in simplified theoretical models of the nebula. The recent radio and IR observations of the Crab suggest, contrary to what has been assumed in the most popular models, that the radio emitting electrons are accelerated now in the same region as the ones responsible for the optical to X-ray emission. All these findings provide important clues about the general physical processes such as self-collimation and energy dissipation in high-velocity, magnetized outflows. I discuss the magnetohydrodynamic structure of the pulsar wind and energy transformation processes both in the wind and in the surrounding nebula. The aim of my talk is to demonstrate that one can account for the new observational results with standard assumptions about the pulsar wind.

### Notes:

Submitted by Yuri Lyubarsky [lyub@bgumail.bgu.ac.il]

## 5.3 Pulsar parallaxes, bow shock nebulae and the interstellar medium

*S. Chatterjee, J. M. Cordes*

### Abstract:

Bow shocks and pulsar wind nebulae probe the interaction of neutron star relativistic winds with the interstellar medium. We utilize scaling laws derived for bow shock nebulae, in combination with estimates of neutron star distances and velocities, to extract information about the interstellar medium as well as relativistic winds. Specifically, we report on Hubble Space Telescope and Chandra observations of the spectacular Guitar Nebula, produced by a high velocity but otherwise unremarkable neutron star. The observed time evolution in the position and morphology of the nebula leads us to infer the existence of small scale density fluctuations in the interstellar medium, while X-ray observations reveal potential evidence for magnetic reconnection. Increases in the sample of precise astrometric measurements, coupled with multi-wavelength observations, will enable a deeper understanding of neutron star relativistic winds: we introduce an ongoing project with the Very Long Baseline Array, which is expected to at least double the number of measured pulsar parallaxes in the next two years.

### Notes:

Submitted by Shami Chatterjee [schatterjee@aoc.nrao.edu]

## 5.4 X-ray spins and radio speeds: probing pulsar birth kinematics with Chandra and the Very Long Baseline Array

*W. Brisken (NRAO), R. Romani (Stanford University)*

### Abstract:

The origin of the enormous momentum kicks imparted to pulsars at birth is one of the outstanding problems in core collapse physics. Recent advances in imaging the toroidal structures in pulsar wind nebulae (with Chandra) and in obtaining interferometric proper motions (with the Very Long Baseline Array) have made it possible to compare the linear and angular momentum vectors of several young pulsars. We describe here our Chandra imaging/Very Long Baseline Interferometry campaign for two pulsars in nearby supernova remnants: PSR J0538+2817 in S147 and PSR B1706-44 in G343.1−2.3. These objects are particularly interesting since apparent spin-velocity alignment and large initial spin periods allow a significant test of kick models. We show that the data should allow a comparison of the projected spin and kick axes at the 3 degree level, comment on the implications for the pulsar/supernova remnant associations and discuss briefly the implications of such measurements for neutron star kick physics.

### Notes:

## 5.5 Radio investigation of ultraluminous X-ray sources

*Neal Miller, Susan Neff, Richard Mushotzky*

### Abstract:

The high resolution of Chandra has yielded an abundance of discrete X-ray sources in nearby galaxies. The most extreme of these have X-ray luminosities in excess of the Eddington limit for stellar mass objects. Called "intermediate X-ray objects" (IXOs) or "ultraluminous X-ray sources" (ULXs), these enigmatic sources may be intermediate mass black holes emitting isotropically or stellar mass compact objects with beamed emission. To date, most of the follow-up of ULXs has occurred at X-ray and optical wavelengths. We are engaged in a project to analyze the radio properties of known ULXs. Radio data provide a particularly powerful avenue for the understanding of ULXs, potentially discriminating between beamed and unbeamed progenitors and providing estimates of source lifetimes and total energies. Relying on archival VLA data, we have identified numerous ULXs with associated radio emission. Our preliminary results will be discussed.

### Notes:

Submitted by Neal Miller [nmiller@h2.gsfc.nasa.gov]

## 5.6 Ain't no Crab, PWN got a brand new bag: correlated radio and X-ray structures in pulsar wind nebulae

*M. Roberts, M. Lyutikov, C. Tam, B. Gaensler, C. Brogan, R. Romani*

### Abstract:

The traditional "bag" model of radio pulsar wind nebulae (PWN), encouraged by the amorphous shape of the Crab radio nebula, is where the radio nebula is simply the historical repository of the pulsar wind and is largely unaffected by recent pulsar activity. Observations of several PWN, both stationary (sPWN) and rapidly moving (rPWN), now show clear morphological relationships between structures in the radio and X-ray. Sometimes these are correlations, sometimes anti-correlations, but it is apparent that X-ray structures are often associated with radio intensity variations on the order of unity. These require local magnetic field enhancements which are related to the present-day wind activity and can potentially be used to probe the structure of the pulsar wind. We present high-resolution X-ray and radio images of several PWN of both types and discuss the morphological relationships between the two wavebands. In the case of the sPWN in SNR G11.2-0.3, there are structures seen out to the very edges of the PWN which seem like they must be related to the configuration of electrical currents in the near wind-zone of the pulsar.

### Notes:

Submitted by Mallory Roberts [roberts@physics.mcgill.ca]

## Session 6

# X-Ray and Radio Observations

## 6.1 Mining the X-ray archives at the HEASARC: a users guide

*Stephen A. Drake*

### Abstract:

The High Energy Astrophysics Science Archive Research Center (HEASARC) is NASA's designated archive for cosmic X-ray, $\gamma$-ray and EUV data from missions such as XMM-Newton, Chandra, ROSAT, CGRO, etc. It also provides web tools and distributed software packages to help in the analysis of these datasets, e.g. HEASoft (which includes FTOOLS and XSPEC). I will give a high-level overview of the HEASARC's services.

### Notes:

Submitted by Stephen Drake [drake@olegacy.gsfc.nasa.gov]

## 6.2 Mining radio archives

*Michael Rupen*

### Abstract:

Much of the radio sky is lying in data archives awaiting the intrepid astronomer. The VLA in particular has been in operation for more than a quarter century, and the archive contains the raw material for innumerable summer student projects, PhD theses, and possibly even the odd Nobel Prize. It also contains the data you ought to examine before writing a proposal requesting 1000 hours to detect source X. Using real examples I will demonstrate how to find the data relevant to your source, and briefly discuss the resources NRAO provides to get you from the raw bits to a beautiful image.

### Notes:

Submitted by Michael Rupen [mrupen@aoc.nrao.edu]

## 6.3 Preparing a competitive radio proposal

*Ed Fomalont*

### Abstract:

The success in obtaining observation time for a peer-reviewed scientific radio proposal depends on the importance of the scientific goal, and its appropriateness for the designated radio telescope. Other proposal properties, like the clarity and succinctness of the write-up, are also important and need little more discussion. However, some predilections of the observatory and the people who evaluate radio proposals and allocate the observing times may not be obvious to the first-time radio proposer. So, we present some suggestions, based on several decades of proposal submissions and rejections, for increasing your chance at obtaining radio observation time. We will concentrate on the Very Large Array as the radio instrument and a few of the topics discussed are: do not lecture the referees with knowledge they already have; be as flexible as possible; propose well before the deadline; discuss (or get advice) for possible technical problems. Other useful information about the proposal and observing cycles, and financial support from the National Radio Astronomy Observatory are included.

### Notes:

Submitted by Ed Fomalont [efomalon@nrao.edu]

## 6.4 How to write a good proposal for X-ray observations

*Fred Seward*

### Abstract:

The proper form and content of a good proposal will be described and illustrated with particularly bad examples taken from the first five cycles of the Chandra Program. The proposal process will be explained from the viewpoint of the review organizers and that of the review panel. Practical suggestions for improving your chance of success will be given.

### Notes:

Submitted by Fred Seward [fds@cfa.harvard.edu]

## 6.5 The Green Bank Telescope

*Felix J. Lockman*

### Abstract:

The Green Bank Telescope is a powerful new instrument for radio astronomy. This poster will summarize some of the telescope's properties that are relevant to X-ray astronomy, and will discuss some early scientific results. It is currently detecting radio counterparts to X-ray pulsars in a variety of environments, and with sensitive bolometer arrays it will be able to image the S-Z effect in distant clusters at 7" angular resolution. Its high dynamic range can reveal extended structures around SNRs. It can provide accurate estimates of galactic foregrounds through observation of the 21cm line, and add considerable sensitivity to very long baseline arrays.

### Notes:

Submitted by Felix Lockman [jlockman@nrao.edu]

## Session 7

# Dissipation of Jets

## 7.1 Theory of jet dissipation

*David S. De Young*

**Abstract:**

An understanding of the physical processes by which collimated astrophysical flows lose their initial momentum and transfer mass and energy to their environment ("jet dissipation") is perhaps the only means by which we will be able to determine the mass and energy fluxes contained in these objects. This review will focus on the physics of jet dissipation and in particular on those mechanisms that appear to be universal and/or more or less inevitable in mediating jet dissipation. Both hydrodynamic and magnetohydrodyamic processes will be discussed, including the results of non-linear calculations. In addition to such continuous jet dissipation processes, some discussion will be given to mechanisms for sudden jet disruption and to the final evolution of jet-produced lobes and their influence on jet dissipation. The use of extant or future observational data to discriminate among dissipation processes will also be included.

**Notes:**

Submitted by David De Young [deyoung@noao.edu]

## 7.2 Observations of jet dissipation

*Robert Laing*

### Abstract:

I will briefly review the observations of X-ray emission from radio jets, hot-spots and lobes in extragalactic radio sources and their immediate implications. I will then describe in more detail some recent results on the deceleration of relativistic jets in Fanaroff & Riley type I radio galaxies, which provide a detailed picture of their velocities, magnetic-field and emissivity distributions and mass entrainment rates. I will emphasize the importance of X-ray observations, not only in identifying regions of ongoing particle acceleration but also in quantifying the external density and temperature.

### Notes:

Submitted by Robert Laing [rlaing@eso.org]

## 7.3 Jet dissipation and particle acceleration

*M.J. Hardcastle*

### Abstract:

I will discuss X-ray synchrotron emission as a probe of particle acceleration, concentrating mainly on low-power (Fanaroff & Riley type I) jets. Combining X-ray and radio data has allowed us to locate the sites of high-energy particle acceleration, and hence jet kinetic energy dissipation, in a number of objects. Recent data solve some old problems but present some new ones.

### Notes:

Submitted by Martin Hardcastle [m.hardcastle@bristol.ac.uk]

## 7.4 Radio jets in cooling cores

*Jean Eilek*

### Abstract:

The X-ray loud atmosphere in many rich clusters of galaxies contains a strong central density cusp, in which the radiative lifetime is short compared to the age of the cluster. These are called "cooling cores"; their energetics and thermal structure are not understood. We now know that a currently active radio galaxy sits at the center of almost every cooling core. Combining radio and X-ray images reveals the dramatic interaction which is taking place between the radio jet and the central cluster plasma. At least two important questions can in principle be answered by comparing the new data to theoretical models. One is how the radio jet propagates, and disrupts, in the cooling core environment: why are these cluster-center radio sources unusual? The second is the effect the radio jet has on the cooling core: is it energetically important to the core? In this talk I will present a few case studies in detail, and also consider what can be learned from the larger samples which are currently being studied.

### Notes:

Submitted by Jean Eilek [jeilek@aoc.nrao.edu]

## 7.5 Combined synthetic X-ray and radio observations of simulated radio jets

*I. L. Tregillis, T. W. Jones, Dongsu Ryu*

### Abstract:

I will present results from an extensive synthetic observation analysis of numerically-simulated radio galaxy jets. This is the first such analysis of its kind, based on simulations with sufficient physical detail to allow the application of standard observational analysis techniques to simulated radio galaxies. In this talk I will focus on extracting magnetic field properties from nonthermal intensity information, comparing field values obtained via the combination of synchrotron radio and inverse-Compton X-ray data to those from the minimum-energy approach. The combined radio/X-ray technique provides meaningful information about the field, although care is required when applying the results quantitatively. The minimum-energy approach retrieves reasonable field estimates in regions physically close to the minimum-energy partitioning, though the technique is highly susceptible to deviations from the underlying assumptions. Biases in minimum-energy field estimates reflect actual differences from the equipartition condition. Finally, I will show how the two field measurement techniques might be combined to provide a rough measure of the actual energy in particles and fields. A full report on this work will appear in the Astrophysical Journal, v601 n2 February 1, 2004.

### Notes:

## 7.6 Jet/environment interactions of FR-I and FR-II radio galaxies

*J.H. Croston*

### Abstract:

I shall present the results of new XMM observations of Fanaroff & Riley type I (FR-I) and FR-II radio galaxies that show the importance of jet/environment interactions for both radio-source structure and the properties of the surrounding gas. The FR-I observations reveal that the distribution of hot gas determines the radio-lobe morphology, and provide evidence that the subsonic expansion of the lobes heats the surrounding gas. The FR-II observations constrain the properties of the medium confining the radio source and show that shock heating is important. Finally, I shall present analysis of a sample of elliptical-dominated groups, in which 40 percent of the groups contain a radio galaxy that appears to be affecting the group gas properties.

### Notes:

Submitted by Judith Croston [judith.croston@bristol.ac.uk]

## 7.7 Interaction of jets with inhomogeneous interstellar media

*G.V. Bicknell R.S. Sutherland C.J. Saxton*

### Abstract:

We have been conducting simulations of jets passing through inhomogeneous interstellar media. These simulations are relevant to jets in young GHz-peaked spectrum (GPS) and compact steep spectrum (CSS) radio galaxies and to the evolution of jets and radio lobes in cooling flow galaxies. The simulations are both 2D and 3D. The 3D simulations have a resolution of 512*512*512. The resulting morphology of the radio source depends upon the power of the jet and the filling factor of clouds. Morphologies strongly resembling classic sources such as 3C48, M87 and 3C84 as well as numerous GPS and CSS sources and Seyfert galaxies are produced. In addition the simulations preeict that in some cases, additional low surface brightness radio plasma will be present on larger scales than revealed by current images. This may be particularly relevant to high redshift radio galaxies. The dissipation resulting from the radio plasma-interstellar medium interaction gives rise to shocked emission lines and heating of the tenuous interstellar medium. The implications of this for the heating of cooling flows by radio plasma will be discussed.

### Notes:

Submitted by Geoffrey Bicknell [geoff@mso.anu.edu.au]

## 7.8 The radio/X-ray connection in Abell 2029

*T.E. Clarke, E.L. Blanton, & C.L. Sarazin (Univ. of Virginia)*

**Abstract:**

Recent advances in the sensitivity and resolution of X-ray observatories have revealed a vast array of complex physics at work in galaxy clusters. One of the most spectacular results is the profound effect that the cluster-center radio sources appear to have on the thermal gas in the dense cluster core. In many clusters with very dense cores, the X-ray emission shows depressions surrounded by bright rims of gas. These dense cluster cores are often host to powerful radio galaxies. Comparison of the radio and X-ray emission shows that the radio lobes appear to fill the depressions, suggesting that the synchrotron plasma has pushed aside the thermal gas. The bright radio rims are generally found to be composed of cool, dense gas rather than hot shocked emission. We present results of an analysis of the central regions of Abell 2029 and discuss the connections between the radio and X-ray components of the cluster. The Chandra observations reveal a number of bright X-ray filaments extending outward from the cluster core. Several of these filaments appear to be connected to the steep-spectrum radio source PKS 1509+59 located in the core of the cluster. An analysis of the temperature structure in the cluster shows that the southern extension of PKS 1509+59 is surrounded by cool X-ray gas. The northern lobe, however, does not appear to be connected to cool gas. We will also discuss the inner regions of the radio source which show two oppositely-directed, collimated jets that disrupt as the jets apparently encounter a drop in the confining thermal plasma.

**Notes:**

Submitted by Tracy Clarke [tclarke@virginia.edu]

## 7.9 The jet/ISM interaction in three nearby radio galaxies as seen with Chandra

*R. P. Kraft, W. R. Forman, E. C. Churazov, M. J. Hardcastle, S. Heinz, C. Jones, M. Markevitch, S. S. Murray, P. A. J. Nulsen, A. Vikhlinin, D. M. Worrall*

**Abstract:**

Chandra observations of radio galaxies have demonstrated a wide range of complex interactions between their jets and the ambient interstellar medium(ISM)/intercluster medium. In this presentation, we will discuss results from Chandra observations of jet/lobe interactions with the ambient medium in three nearby radio galaxies: Centaurus A (at a distance of 3 Mpc), M87 (17 Mpc), and NGC507 (67 Mpc). We will present the observations for each object and relate them to the more general picture of jet/ISM interactions. In Centaurus A, we have detected a hot, dense shell of gas surrounding the SW radio lobe. We attribute the shell to the supersonic expansion of the lobe into the ISM. There is low-luminosity evidence of a similar interaction around the northeast radio lobe. We discuss the implications of this shell and the asymmetry. A publicly-available deep Chandra observation (100 ks) of M 87 indicates complex structures over a range of scales. Features include several X-ray cavities related to the radio cocoon in the central 45", an X-ray cavity coincident with a radio bubble that lies perpendicular to the jet/counter jet axis suggestive of a buoyant bubble, and several roughly concentric surface brightness discontinuities in the larger scale gas indicative of multiple radio outbursts. Chandra observations of NGC507 have detected a large surface brightness discontinuity related to the expansion of the radio lobes. The appearance of this feature is most likely due to the entrainment of higher abundance gas from the central regions of the galaxy as the lobe expands at roughly the sound speed of the ambient gas.

**Notes:**

Submitted by Ralph Kraft [rkraft@cfa.harvard.edu]

## 7.10 Radio and X-ray images of radio galaxy and quasar jets generated by moving source of relativistic electron injection

*E.Yu. Bannikova and V.M. Kontorovich*

### Abstract:

Radio galaxies and quasars are examined now with high angular resolution in a wide frequency interval from radio waves to X-ray. In some of them there are jets with local knots and hot spots, which often have fine structure in the form of asymmetric "flares", that may be interpreted as a result of movement of knots or hot spots. The difference of jet images of extragalactic sources in radio and X-ray bands and thence obtaining some additional information on physical conditions in the sources is discussed. The investigation was carried out within the diffusion model of propagation of relativistic electrons from the jet knots and hot spots with Compton and synchrotron losses considered. We use the kinetic equation describing these processes for the distribution function of relativistic electrons with a given moving source and with restriction to diffusion as a mode of electron propagation (Valtaoja 1982, Gestrin et al 1987). The similarity and distinction between the images of jets of extragalactic sources in a radio and X-ray bands created by the same distribution of relativistic electrons due to synchrotron (for radio) and inverse-Compton scattering (for X-ray) is discussed (Bannikova & Kontorovich 2003). The case of independent of coordinates purely Compton losses on relic radiation is considered. It is shown, that the heterogeneity of a magnetic field can result in characteristic differences in the form and location of R- and X- isophotes depending from that the magnetic field decreases or increases to the periphery of the source. 1. E.Valtaoja. Astron. & Astrophys. 1982, 111, 2, pp.213-219. 2. S.G. Gestrin, V.M. Kontorovich, A.E. Kochanov. Kinematica i fizika nebesnyh tel,1987, 3, 4, pp.57-66. 3. E.Yu. Bannikova, V.M. Kontorovich In: JENAM 2003, 2003, Abstracts, Budapest. p.12.

### Notes:

Submitted by Elena Bannikova [bannikova@astron.kharkov.ua]

## 7.11 XMM-Newton observations of high redshift radio galaxies

*Elena Belsole*

### Abstract:

I will present results on the physical states of three high-redshift powerful radio galaxies (3C292 at z=0.7, 3C184 at z=1, and 3C322 at z=1.7). They were obtained by combining radio measurements with X-ray measurements from XMM-Newton that separate spectrally and/or spatially radio-related and hot-gas X-ray emission. Originally observed as part of a programme to trace clusters of galaxies at high redshift, none of the sources is found to lie in a rich X-ray-emitting environment similar to those of some powerful radio galaxies at low redshift, although the estimated gas pressures are sufficient to confine the radio lobes. The weak gas emission is a particularly interesting result for 3C184, where a gravitational arc is seen, suggesting the presence of a very massive cluster. Here Chandra data complement the XMM-Newton measurements in spatially separating X-ray extended emission from that associated with the nucleus and rather small radio source. 3C292 is the source for which the X-ray-emitting gas is measured with the greatest accuracy, and its temperature of 2 keV and luminosity of $6 \times 10^{43}$ erg/s are both characteristic of a poor cluster. This source allows the most accurate measurement of inverse-Compton X-ray emission associated with the radio lobes. In all structures where the magnetic-field strength can be estimated through combining measurements of radio-synchrotron and inverse-Compton-X-ray emission, the field strengths are consistent with sources being in a state of minimum total energy.

### Notes:

Submitted by Elena Belsole [e.belsole@bristol.ac.uk]

## 7.12 Analytical modeling of young radio sources and their synchrotron spectra

*R. Bolton, P. Alexander*

**Abstract:**

We have recently extended analytical models of radio-source growth down to very young sources where the jets are still un-collimated. These models continue to hold as the sources expand and the jets become collimated. Predictions of the synchrotron/self-absorption spectra as sources grow are made and ages of real sources inferred.

**Notes:**

Submitted by Rosie Bolton [r.bolton@mrao.cam.ac.uk]

## 7.13 Radio and X-ray observations of 3C15 and 3C303

*P.G. Edwards and J. Kataoka*

### Abstract:

We report the Chandra detection of a X-ray kpc-scale jet components in 3C15 and 3C303. In 3C15, the peak of the X-ray emission in the jet is 4.1 arcsec from the core, and coincident with a component previously identified in the radio and optical jets. The X-ray morphology of 3C303 is similar to that of the radio/optical emission with peaks in the X-ray emission found at 5.5, 9 and 17 arcsec from the core. We construct the spectral energy distributions for components in these sources and find that the X-ray fluxes are well below the extrapolation of the radio-to-optical continuum. We provide interpretations of these observations, and describe planned Very Long Baseline Interferometry observations to study the parsec scale jet morphology. Our observations confirm that particles are accelerated very efficiently in radio galaxies.

### Notes:

Submitted by Phil Edwards [pge@vsop.isas.jaxa.jp]

## 7.14 Continuing a Chandra survey of X-ray counterparts of quasar radio jets

*Jonathan Gelbord (MIT), H.L. Marshall (MIT), D.A. Schwartz (SAO), D.M. Worrall (SAO & Bristol), M. Birkinshaw (SAO & Bristol), J. Lovell (CSIRO), D. Jauncey (CSIRO), E. Perlman (UMBC), D. Murphy (JPL), R.A. Preston (JPL)*

### Abstract:

We are conducting an X-ray survey of flat-spectrum radio quasars, selected by properties of their extended radio flux. We present the results from the first stage of our survey, as well as new X-ray images obtained since November as part of the continuation of our sample. Chandra snapshot imaging observations provide detections of X-ray counterparts to the radio jets in about two thirds of our sources (13 of first 20 observed). We compare the detailed morphology of the radio and X-ray structures and construct broadband spectral energy distributions to elucidate the X-ray emission processes and to constrain the physical conditions within the jets. We find that inverse-Compton scattering of cosmic microwave background flux best characterizes the X-ray emission. Jet parameters are typically $B_{eq} \sim 10^{-5}$ Gauss, $\Gamma \sim$ few to ten, and $\Theta_{max} \sim 10°$.

### Notes:

Submitted by Jonathan Gelbord [jonathan@space.mit.edu]

## 7.15 Witnessing the gradual slow-down of powerful extragalactic jets: The X-ray - radio connection

*Markos Georganopoulos & Demosthenes Kazanas*

### Abstract:

Radio jets emanating from the central engine of powerful active galaxies start with relativistic velocities, as indicated by the superluminal velocities observed in their inner (pc) part. However, it is still not clear if the jets remain relativistic further out, a key question for their dynamics. Recently, it was shown that the Chandra-detected X-ray emission from knots in large scale ($\sim$ hundreds of Kpc) powerful jets is best understood as Compton scattering off the Cosmic Microwave Background from jets that flow relativistically (Lorentz factor $\sim$ 10-20). A puzzling feature of this X-ray emission is that it peaks in the inner part of the jet, decreasing outward, a behavior markedly opposite to that of the radio emission. Here we show that, this naturally results form a gradual deceleration of the jet flow, and that the offsets between different wavelength maps can reveal the deceleration profile. This matches another recent finding, namely that the jet flow feeding the hot spots - bright regions where the jets terminate colliding with the Intergalactic Medium - is still relativistic with a Lorentz factor of $\sim$ a few.

### Notes:

Submitted by Markos Georganopoulos [markos@milkyway.gsfc.nasa.gov]

## 7.16 The enigmatic X-ray jet of 3C120

*D.E. Harris, R. C. Walker, and A. E. Mossman*

### Abstract:

Using recently acquired Very Large Array data at 15 and 43 GHz, older Very Large Array data between 1.4 and 15 GHz (Walker and colleagues), and archival Chandra observations, we revisit the long standing problem of the X-ray emission mechanism for a knot 25" from the core of 3C120 ('k25') where the jet appears to suffer a deflection towards the North. With the factor of 10 improvement in angular resolution of Chandra over the ROSAT/HRI data, we are able to examine 3 regions within k25. On the basis of source morphology and the shape of the radio to X-ray spectrum, we calculate the key parameters for several emission mechanisms. These are compared to the same parameters for a few other jet features closer to the core. We conclude that no simple emission mechanism fits all features but that synchrotron emission from an electron distribution that departs from a (broken) power law is favored over thermal or inverse-Compton models. The work at SAO was supported by NASA contract NAS8-39073. The National Radio Astronomy Observatory is a facility of the National Science Foundation operated under cooperative agreement by Associated Universities, Inc.

### Notes:

Submitted by Dan Harris [harris@cfa.harvard.edu]

## 7.17 X-ray measurement of particle and field energy distributions in lobes of radio galaxies

*Naoki Isobe, Kazuo Makishima, Makoto Tashiro, Naoko Iyomoto, Hidehiro Kaneda, Masaya Suzuki, Abe Keiichi, Masanori Mori*

### Abstract:

We report the measurement of particle and field energy densities in lobes of a number of radio galaxies, through the detections of inverse-Compton X-ray emission with ASCA, Chandra and XMM-Newton. We have discovered the following three important results. The first is that the electron energy density usually dominates the magnetic field by an order of magnitude. The second is that the electron dominance in the lobes seems to increase when the nucleus is more active in X-rays. The third is that in several lobes the electrons are rather uniformly distributed over the lobes while the magnetic field becomes stronger toward the lobe periphery. These three discoveries may imply that the electrons play a more important role than the magnetic fields in the evolution of the lobes, in addition to their their role in jet formation, although a larger sample is still needed.

### Notes:

Submitted by Naoki Isobe [isobe@oasis.tksc.jaxa.jp]

## 7.18 A search for X-ray variability in the jet of 3C273

*S. Jester, D. E. Harris, H. L. Marshall, K. Meisenheimer, R. A. Perley, H.-J. Röser*

### Abstract:

We present results from the first of our four Chandra monitoring observations of the jet in 3C273, obtained in November 2003. The initial comparison with archival data from June 2000 shows mildly significant changes in the flux of several parts of the jet. The variability is non-uniform in position and energy space. We will present results of a more detailed determination of flux and spectral variability. SJ was supported in part by the U.S. Department of Energy under contract No. DE-AC02-76CH03000. HLM was supported by the Smithsonian Astrophysical Observatory (SAO) contract SV3-73016 for the Chandra X-Ray Center (CXC). DEH is partially supported by NASA contract NAS8-39073.

### Notes:

Submitted by Sebastian Jester [jester@fnal.gov]

## 7.19 Hydra A: a new picture

*W.M. Lane, T.E. Clarke, G.B. Taylor, R.A. Perley, N.E. Kassim*

### Abstract:

We present new, low-frequency images of the powerful Fanaroff & Riley type I radio galaxy Hydra A (3C218), which lies at the center of the poor Abell cluster A780. Images were made with the Very Large Array at frequencies of 1415, 330, and 74 MHz, with resolutions on the order of 20″. The morphology of the source is seen to be more complex and larger than previously known, and extends nearly 8′(530 kpc) in a North-South direction. The southern lobe is bent to the east and extends in that direction for nearly 3′(200 kpc). We find that the northern lobe has a flatter spectral slope than the southern lobe, consistent with the appearance of greater confinement to the south. A comparison to X-ray observations of the thermal gas in this system shows that Hydra A is surrounded by dense, cool gas which extends well beyond the bright radio jets and is roughly aligned with the low frequency outer emission. This may be entrained cluster core gas which has been dragged out by buoyantly rising outer lobes. Basic research in astronomy at the Naval Research Laboratory is funded by the Office of Naval Research.

### Notes:

## 7.20 X-ray spectroscopy of radio galaxy 3C120

*P. Ogle, S. Davis, R. Antonucci, J. Colbert, M. Malkan, M. Page, T. Sasseen, M. Tornikoski*

### Abstract:

We present a long XMM-Newton observation of the superluminal radio source 3C120. X-ray spectroscopy of the Fe K$\alpha$ line is used to constrain the properties of the accretion disk. Supporting multiwavelength observations show that we caught 3C120 during a radio outburst. We speculate about the connection between accretion disk structure and radio jet formation in active galactic nuclei.

### Notes:

Submitted by Patrick Ogle [pmo@sgra.jpl.nasa.gov]

## 7.21 A multifrequency study of extragalactic jets

*Alberto Sadun*

### Abstract:

In this study we construct and present a database of more than 60 extragalactic jets for analysis, that have been observed in the radio and either optical or X-ray wavebands. The database includes important categories such as length, power, redshift, Fanaroff-Riley type (FR), spectral indices, radiation mechanisms, among others. The purpose of studying jets at widely spaced frequencies with this database is several-fold. First and foremost, by developing correlations and statistics among the various parameters one can further define and delineate the FR I/FR II dichotomy. Indeed, we found that there is a strong correlation between the inverse-Compton process and FR II jets. Secondly, we can use this database to identify X-ray and optical candidates for further study with Hubble Space Telescope, Chandra, and XMM-Newton. Thirdly, we can identify and further process archival data (obtained from VLA, Hubble Space Telescope, and Chandra archival databases) for many of these objects. As a proof of concept, we did just this with 4C30.31, through use of sophisticated image processing techniques, and the results are included. Finally, we can identify optical candidates for searches with ground-based telescopes to look for optical counterparts to radio and X-ray jets. Again, as a proof of concept, we did this for three objects: 3C9, 3C219, and B2 0738+313. Interim results and conclusions of this on-going project will be presented.

### Notes:

Submitted by Alberto Sadun [asadun@carbon.cudenver.edu]

## 7.22 Resolving non-thermal X-ray knots at the Galactic center region with Chandra deep exposure observation

*Atsushi Senda, Shin-ichiro Takagi, Aya Bamba, Katsuji Koyama, (Kyoto University) and Hiroshi Murakami (ISAS/JAXA)*

### Abstract:

We have analyzed the ~0.6 megasecond *Chandra* deep exposure data and resolved several non-thermal X-ray knots located near the Galactic center (GC). In particular, we found three prominent X-ray knots which are aligned from the GC to the north-northwest direction. All of the three X-ray knots have an elongated shape toward the same direction (from GC to north-northwest). The major and minor axes of these knots are typically $\sim 6''$ and $\sim 2.5''$. These spatial features suggest that these knots are jet-like objects ejected from the GC about decades to hundreds years ago. The X-ray spectrum of each knots exhibits no line emissions, hence their origin should be non-thermal. By comparing a Very Large Array 6cm continuum map, we find radio structures are marginally coincident with these X-ray knots.

### Notes:

Submitted by Atsushi Senda [senda@cr.scphys.kyoto-u.ac.jp]

## 7.23 Radio and X-ray connection in GPS sources

*Aneta Siemiginowska et al*

### Abstract:

Giga-hertz Peaked Spectrum (GPS) radio sources are powerful emitters in both radio and X-ray bands. Their compact nature provides us with a unique opportunity to study both the expansion of relativistic jets and the active galactic nuclei nuclear environment at an early stage of the radio source activity. Their Very Long Baseline Array morphology often shows core and jet components on the host galaxy scales, while only a handful of GPS sources also have a low surface brightness radio emission on kpc scale. Our Chandra discovery of X-ray jets on 100 kpc scale indicates that some GPS sources are not truly compact, but instead have large scale morphology typical for radio loud quasars. This large scale X-ray emission could be due to inverse-Compton scattering of Cosmic Microwave Background photons on jet electrons and it highlights a population of low energy electrons otherwise "invisible" in radio. Thus the X-ray emission provides a way to separate large scale sources from the GPS sample, which is important for studying active galactic nuclei evolution. Here, I review the results of the Chandra studies of GPS sources. I discuss both the X-ray spectra and morphology focusing on their relation to radio emitting plasma through the Compton process.

### Notes:

Submitted by Aneta Siemiginowska [asiemiginowska@cfa.harvard.edu]

## 7.24 Extended X-ray emissions from the radio galaxies Centaurus B and Fornax A

*Makoto Tashiro, Naoki Isobe, Masaya Suzuki, Kouichi Ito, Keiichi Abe, Kazuo Makishima*

### Abstract:

The inverse-Compton (IC) X-rays from the radio lobes were the long expected in order to determine the energy of electrons and magnetic field in the radio lobes, without assuming the energy equipartition. In addition, the accurate energy measurement is important to estimate the cooling time of the radio lobe, which reflects the history of the nucleus activity. The radio galaxy Fornax A was the first object from which the diffuse IC X-rays were discovered (Kaneda et al. 1995; Feigelson et al. 1995). Following the discovery Iyomoto et al. (1998) found the dimmed nucleus and discussed the activity history estimating the age of the lobe emission using the lobe particle and field energy. Tashiro et al. (2001) revised the age estimation based on their new X-ray imaging analysis. Recently, with Chandra observation of the host galaxy, Kim et al. (2003) revealed a diffuse emission which are not associated with the lobe. They suggested that it was heated during the active phase of the galaxy. In this paper, we show reanalyzed data from Chandra and determine the age of the emission region. By comparing the age estimation with ASCA and results from the east lobe region with Chandra, we discuss the possible history of the nucleus activity. The other radio galaxy, Centaurus B, is the second object that we discovered the IC X-rays from the lobes. The ASCA results firstly showed that the equipartition assumption is not realized in the radio lobes (Tashiro et al. 1998). The conclusion suggest some structures caused of the possible energy flows. We carried out an XMM-Newton observation of this object to reveal the structure of the diffuse emission. With the fine spatial resolution capability, we distinguished a jet-like structure from the terminal lobe-like emission. We also discuss the revised physical parameters in this paper.

### Notes:

Submitted by Makoto Tashiro [tashiro@phy.saitama-u.ac.jp]

## 7.25 VLBI imaging of the X-ray bright lobe hotspot in PKS B2152−699

*S.J. Tingay*

**Abstract:**

Wide-field Very Long Baseline Interferometry imaging can allow high brightness temperature radio hotspots in radio galaxy jets to be resolved and studied in detail. PKS B2152−699 is a nearby powerful radio galaxy that has been imaged in this way, resolving the southern lobe hotspot that has also been detected with Chandra. Implications of the observed radio and X-ray emission for the X-ray emission mechanism will be explored.

**Notes:**

Submitted by Steven Tingay [stingay@astro.swin.edu.au]

## 7.26 Detection of the active nucleus of M32

*James S. Ulvestad, Luis C. Ho, and Yuichi Terashima*

### Abstract:

M32 hosts a 2.5 million solar mass central black hole, but signs of nuclear activity in this galaxy have long eluded detection. We have detected the M32 nucleus in X-rays based on high-resolution Chandra imaging; the nuclear luminosity of $9.4 \times 10^{35}$ ergs/s is only $3 \times 10^{-9}$ times the Eddington luminosity of the central black hole. A sensitive Very Large Array radio continuum image places a $5\sigma$ upper limit of 30 microJy on the 8.4 GHz radio emission from M32. The low X-ray and radio luminosities constrain the bolometric luminosity to be $\sim 2 \times 10^{-8}$ times the Eddington luminosity. This implies that most of the gas that should be present from stellar mass loss is either accreted with low radiative efficiency or escapes accretion altogether.

### Notes:

Submitted by James Ulvestad [julvesta@nrao.edu]

## 7.27 Large scale radio jets in the galaxy cluster Abell S0102

*Miroslav Filipovic (University of Western Sydney), Edward Waluska (University of South Africa), Derck Smits (University of South Africa), Paul Jones (Australia Telescope National Facility)*

### Abstract:

We present our high resolution radio-continuum study of the radio galaxy jets in the galaxy cluster Abell S0102. We observe this cluster at wavelengths of $\lambda$=20/13 and 6/3 cm with the 6 km array using the Australia Telescope Compact Array (ATCA). With these configurations, we can achieve a resolution of $\sim$ 1 arcsec which is sufficient to resolve the jet-like structure of $\sim$ 3 arcminute length detected at 20 cm and centered on the merger cluster galaxy ESO 295-IG022-1. These observations, in addition to our observations at other wavelengths (ROSAT), allowed us to further our studies on the nature of jet-like emission in this complex galaxy cluster. Also, we will present our study of the magnetic field as well as the spectral index distribution along the extended jet.

### Notes:

Submitted by Edward Waluska [ewaluska@dc.rr.com]

## 7.28 Cen A's interaction with X-ray-emitting ISM

*D.M. Worrall, R.P. Kraft, M. Birkinshaw, M.J. Hardcastle, W.R. Forman, C. Jones, S.S. Murray*

### Abstract:

As the closest radio galaxy, Centaurus A is a powerful laboratory for the X-ray study of radio-emitting structures and their interactions with the hot interstellar medium. This poster will present the remarkable X-ray enhancement which caps the inner southwest radio lobe. This shell is hotter, and greatly overpressurized, relative to the ambient ISM, and we interpret it as evidence for heated, compressed, material behind the bow shock of a radio lobe which is advancing supersonically. We highlight possible shortcomings in the arguments we use to estimate the advance speed of the lobe, and indicate how studies of supernova remnants may elucidate the applicable physics. It is surprising that it is in Cen A, a relatively low-power radio galaxy, that such supersonic lobe expansion has first been detected. Our results demonstrate that the Cen A radio jet is actively re-heating nearby X-ray-emitting gas.

### Notes:

Submitted by Diana Worrall [d.worrall@bris.ac.uk]

## 7.29 A large radio outburst correlated with the large X-ray flare from Sgr A* on 2002-10-3

*Jun-Hui Zhao, R. M. Herrnstein, G. C. Bower, W. M. Goss, & S. M. Liu*

### Abstract:

A large radio outburst at 7mm from Sgr A* was observed during the Very Large Array weekly monitoring program at 2 cm, 1.3 cm and 7 mm, coincident with the largest X-ray flare detected to date with the XMM-Newton X-ray Observatory on 2002-10-03. The X-ray flare appears to be special in many aspects. Besides the high luminosity and softer spectrum at X-ray, a large radio outburst at 7mm was detected within the same day showing the radio spectral index $\alpha = 2.5^{+0.3}_{-0.6}$ ($S \propto \nu^{\alpha}$), consistent with an optically thick nonthermal synchrotron source. Based on numerous observations over hundred hours at X-ray searching for X-ray flares and the weekly Very Large Array monitoring observations over the past three years, the two large events observed at radio and X-ray appear to be correlated. Since the radio source is well confined within a size of 50 Schwarzchild radius of the black hole with a mass of 4 million solar masses, the correlation is the first evidence for that the X-ray flare arises from the inner region of the accretion flow near the event horizon of the supermassive black at the Galactic center rather than from star-star collision or from the heated part of the disk via star-disk interaction. These results suggest that energetic electrons responsible for the radio outburst might be produced via a process associated with the X-ray flare, then transported to large radii, producing the observed radio outburst.

### Notes:

Submitted by Jun-Hui Zhao [jzhao@cfa.harvard.edu]

## Session 8

# Cluster Mergers

## 8.1 Mergers and non-thermal processes in clusters of galaxies

*Craig L. Sarazin*

### Abstract:

Clusters of galaxies generally form by the gravitational merger of smaller clusters and groups. Major cluster mergers are the most energetic events in the Universe since the Big Bang. The basic properties of cluster mergers and their effects will be discussed. Mergers drive shocks in the intracluster gas, and these shocks heat the intracluster gas, and should also accelerate nonthermal relativistic particles. Mergers also produce distinctive features in the X-ray images of clusters, including "cold fronts" and cool trails. Chandra and XMM/Newton observations of the X-ray signatures of mergers will be discussed. X-ray observations of shocks can be used to determine the geometry and kinematics of the merger. As a result of particle acceleration in shocks and turbulent acceleration following mergers, clusters of galaxies should contain very large populations of relativistic electrons and ions. Observations and models for the radio, extreme ultraviolet, hard X-ray, and $\gamma$-ray emission from nonthermal particles accelerated in these shocks will also be described.

### Notes:

## 8.2 Observations of cluster mergers

*Luigina Feretti*

### Abstract:

Recent results on the radio emission from galaxy clusters are presented, with emphasis on the diffuse radio sources associated with the intracluster medium: radio halos and relics. These radio sources demonstrate the existence of large scale cluster magnetic fields and of a population of relativistic particles in the cluster volume. I will discuss the properties of radio halos, the distribution of the radio spectral index, and the comparison between the radio emission and the X-ray emission. The observational results provide evidence that these phenomena are related to cluster merger activity.

### Notes:

Submitted by Luigina Feretti [lferetti@ira.cnr.it]

## 8.3 Energy balance in clusters of galaxies

*Patrick M. Motl and Jack O. Burns*

### Abstract:

I will review, from the point of view of a simulator, physical mechanisms that may be relevant in galaxy clusters in the present Universe. Left to themselves, simulated clusters cool gas in their cores to levels inconsistent with observations. Placing the clusters in a realistic, cosmological context alleviates this problem somewhat through the frequent mergers that reshape rich galaxy clusters. However, the simulations are still inconsistent with observations and it is natural to ask what other mechanisms may play a role. From simple energy constraints, active galactic nuclei are likely to be significant and we explore the case for including active galactic nuclei feedback in galaxy cluster simulations. We also touch on other potentially relevant pieces of physics including feedback from supernovae and thermal conduction. However, if active galactic nuclei are the answer, what then are to be made of clusters that lack evidence for active galactic nuclei activity that nevertheless have canonical cool cores? As cluster samples with high-resolution X-ray data become more common, it is likely to be the properties of relaxed, cool-core clusters that will be the best guides to numerical simulations.

### Notes:

Submitted by Patrick Motl [motl@casa.colorado.edu]

## 8.4 Heating of the ICM due to mixing of fossil plasma

*Matthias Hoeft and Marcus Brueggen*

### Abstract:

Huge amounts of highly relativistic plasma are emitted into the Intra-cluster medium by active galactic nuclei. This plasma rises buoyantly to the fringes of the cluster. However, disruption due to hydrodynamical instabilities slows down the motion of the plasma. Simultaneously, radiative losses cool down the plasma. In the very end the plasma is mixed into the intercluster medium. We calculate the heating rate of the intercluster medium that results from the mixing with the relativistic plasma and the resulting change of the X-ray profiles. We include a discussion of magnetic fields in the plasma which may suppress the disruption.

### Notes:

Submitted by Matthias Hoeft [m.hoeft@iu-bremen.de]

## 8.5 The Sunyaev-Zeldovich effect in nearby massive clusters as observed by the CBI

*S. Myers and the CBI Team*

### Abstract:

The Cosmic Background Imager (CBI) has observed a complete sample of nearby (z<0.1) clusters. Measurements of the Sunyaev-Zeldovich Effect (SZE) in these clusters in the CBI bands from 26-36 GHz, when combined with X-ray imaging and temperatures, provide a determination of cluster baryon density and the Hubble Constant. The latest generation of X-ray satellites and radio instruments can provide important constraints on the cluster astrophysics, such as the effect of mergers and multi-phase media, which will be necessary to realize the goals of using clusters for precision cosmology.

### Notes:

Submitted by Steven Myers [smyers@nrao.edu]

## 8.6 Chandra temperature maps for galaxy clusters with radio halos

*M. Markevitch, F. Govoni, L. Feretti, G. Giovannini*

### Abstract:

We compare Chandra temperature maps and the radio halo maps for a sample of merging clusters including A520, A665, A754, A773, A1914, A2163, A2218, A2319, and 1E0657−56, in order to get empirical insights into the processes responsible for the radio halo generation. Some clusters, e.g., A520, A665, 1E0657−56, exhibit the previously reported spatial correlation between the radio halo brightness and the hot gas regions. However, it is not a general feature, and we find counterexamples (e.g., A754 and A773) where the hottest gas regions do not exhibit radio emission. We will discuss what these findings can tell about the relativistic particle acceleration mechanism operating in clusters.

### Notes:

Submitted by Maxim Markevitch [maxim@head.cfa.harvard.edu]

## 8.7 Computer simulations of nonthermal particle and photon spectra from merging clusters of galaxies

*Robert C. Berrington (University of Wyoming) and Charles D. Dermer (NRL)*

### Abstract:

We have developed a numerical model for the temporal evolution of particle and photon spectra resulting from nonthermal processes at the shock fronts formed in merging clusters of galaxies. Fermi acceleration is approximated by injecting power-law distributions of particles during a merger event, subject to constraints on maximum particle energies. We consider synchrotron, bremsstrahlung, Compton, and Coulomb processes for the electrons, nuclear, photomeson, and Coulomb processes for the protons, and knock-on electron production during the merging process. The broadband radio through $\gamma$-ray emission radiated by nonthermal protons and primary and secondary electrons is calculated both during and after the merger event. We consider the prospects for detecting nonthermal radio and $\gamma$-ray emission from clusters of galaxies and implications for the origin of ultra-high energy cosmic rays and the diffuse $\gamma$-ray background. Cluster merger shocks can accelerate protons to less than $\sim 10^{19}$ eV, and find it difficult to obtain higher energies. We predict that *GLAST* will detect several cluster mergers and, depending on the mean magnetic fields in the intracluster medium, the Low Frequency Array could detect anywhere from several to several hundred.

### Notes:

Submitted by Robert Berrington [rberring@uwyo.edu]

## 8.8 Low frequency radio surveys: searching for cluster halos and relics

*A. S. Cohen, W. M. Lane, T. J. W. Lazio, N. E. Kassim, R. A. Perley, W. D. Cotton, J. Condon, H. J. A. Röttgering, R. Wilman, P. Best, M. Pierre, A. Refregier, M. Birkinshaw, M. Bremer, H. Liang & A. Zanichelli*

### Abstract:

Recent advances in low frequency radio ($\nu < 0.5GHz$) instruments and techniques have made possible deep, high resolution surveys. Such surveys are ideal for finding the diffuse, steep-spectrum radio emission comingfrom halos and relics known to exist preferentially in clusters of galaxieswhich are undergoing major mergers. Here we describe two major surveys currently underway, which have the potential for discovering many such halo/relic systems. The first is the Very Large Array Low-frequency Sky Survey (VLSS) which is a National Radio Astronomy Observatory-Naval Research Lab collaboration to map the entire northern sky at 74 MHz. The second is the XMM Large Scale Structure project (XMM-LSS) in which a 8 x 8 sq. deg. region will be mapped by XMM. The XMM-LSS project includes a low-frequency radio survey at both 325 and 74 MHz in order to compare the location of radio sources and the large scale structure. We describe both surveys, their current progress and identification of halo/relic candidates from the data acquired so far.

### Notes:

Submitted by Aaron Cohen [aaron.cohen@nrl.navy.mil]

## 8.9 Search for TeV emission from galaxy clusters

*B.L. Dingus for the Milagro Collaboration*

### Abstract:

Galaxy clusters are predicted to be emitters of high energy $\gamma$ rays due to the relativistic particles accelerated by merger and accretion shocks. These energetic particles are also invoked in order to explain extended radio halos and hard X-ray spectra. The $\gamma$-rays are produced both by inverse-Compton scattering of relativistic electrons and by high energy proton cascades due to p-p collisions. The TeV fluxes predicted for clusters such as Coma (Miniati, 2003) are near the sensitivity of current and future detectors. In this poster we report upper limits for TeV $\gamma$-ray emission from clusters using data from the Milagro $\gamma$-ray observatory. Milagro is a unique TeV $\gamma$-ray observatory, located in the mountains above Los Alamos, NM, that has a $\sim$ 2sr field of view and $> 90\%$ duty factor, making it ideal for surveying the sky for new classes of TeV astrophysical sources.

### Notes:

Submitted by Brenda Dingus [dingus@lanl.gov]

## 8.10 Simulating the magnetic field in the local supercluster

*K. Dolag, D. Grasso, V. Springel, I. Tkachev*

### Abstract:

We recently performed a magnetohydrodyamic-smoothed particle hydrodynamics (MHD-SPH) simulation of the constrained local universe. This simulation covers the structure of the local universe out to the distance of the Coma cluster. As the initial conditions where constructed using the constrains from the IRAS Galaxies, we are able to identify clusters in our simulation with observed clusters, like Hydra, Coma, Perseus, etc. We can also identify superclusters like the Centaurus super cluster. We already calculated the deflection of ultra high-energy cosmic rays by the magnetic field structure predicted by this simulation (astro-ph/0308155). In my presentation I will focus more on the magnetic field structure in clusters, superclusters and filaments predicted by the simulation (Dolag et al., in preparation).

### Notes:

Submitted by Klaus Dolag [kdolag@pd.astro.it]

## 8.11 Tsunamis in galaxy clusters: heating of cool cores by acoustic waves

*Yutaka Fujita, Takeru Ken Suzuki, and Keiichi Wada*

**Abstract:**

Using an analytical model and numerical simulations, we show that acoustic waves generated by turbulent motion in intracluster medium effectively heat the central region of a so-called "cooling flow" cluster. We assume that the turbulence is generated by substructure motion in a cluster or cluster mergers. Our analytical model can reproduce observed density and temperature profiles of a few clusters. We also show that waves can transfer more energy from the outer region of a cluster than thermal conduction alone. Numerical simulations generally support the results of the analytical study.

**Notes:**

Submitted by Yutaka Fujita [yfujita@th.nao.ac.jp]

## 8.12 The cooling flow cluster Abell 2626 and the associated radio emission

*Gitti M., Brunetti G., Feretti L., Setti G.*

**Abstract:**

We present Very Large Array data at 330 MHz and 1.5 GHz of the radio emission observed in the cooling flow cluster A2626. By producing images at different resolutions we found that the radio source consists of different components: an unresolved core plus a jet-like feature, two elongated parallel features, and an extended diffuse emission (radio mini-halo). Low resolution images allow us to derive morphological and spectral information of the diffuse emission: the radio mini-halo is extended on a scale comparable to that of the cooling flow region and is characterized by amorphous morphology, lack of polarized flux and very steep spectrum which steepens with distance from the center. We then applied to this new mini-halo source a model for particle re-acceleration in cooling flows (Gitti, Brunetti & Setti 2002). In particular, we found that its main radio properties (brightness profile, integrated radio spectrum and radial spectral steepening) can be accounted for by the synchrotron radiation from relic relativistic electrons in the cluster, which are efficiently re-accelerated by magnetohydrodynamic turbulence amplified by the compression of the cluster magnetic field in the cooling flow region.

**Notes:**

Submitted by Myriam Gitti [Myriam.Gitti@uibk.ac.at]

## 8.13 Probing relativistic plasmas in SNRs, radio galaxies, and clusters at low radio frequencies

*Namir E. Kassim, T. Joseph W. Lazio, Wendy Lane, Aaron Cohen, Tracy Clarke, Crystal Brogan*

### Abstract:

High resolution, low frequency radio observations of non-thermal sources such as supernova remnants (SNRs), radio galaxies, and clusters can be a valuable compliment to both higher frequency radio and X-ray observations of these objects. For SNRs they can probe unshocked ejecta, constrain the physics of Fermi acceleration, and delineate the distribution of ionized gas at SNR/molecular cloud boundaries, all of which are well complimented 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 which may not be revealed by higher frequency radio observations. Towards clusters they anchor accurate continuum spectra which can help study the pressure balance between the nonthermal 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. In my presentation I will give examples of how a recent Very Large Array-led renaissance in high resolution, low frequency radio observations are providing new images which can address these questions - observations which foreshadow future significant strides by an emerging generation of low frequency instruments such as the Low Frequency Array (LOFAR).

### Notes:

Submitted by Namir Kassim [namir.kassim@nrl.navy.mil]

## 8.14 An approach based on plasma kinetic theory to the X-ray and radio connection in clusters of galaxies

*N. Okabe and M. Hattori*

### Abstract:

When the temperature inhomogeneity exists in plasma, the electron velocity distribution deviates from the Maxwell-Boltzmann and takes an anisotropic form since a heat flux must have a finite value. The anisotropic velocity distribution function induced by the temperature gradient drives the Weibel-type instability and generates magnetic fields. The growth of the instability is saturated by the wave-particle interaction. After the saturation, the generated small-scale magnetic fields evolve into larger-scale fields via inverse-cascade. This magnetic field generation mechanism predicts that the nature of the cosmic magnetic fields have natural correlation with the thermal nature of the plasma. This mechanism is applied to clusters of galaxies. This mechanism can explain observational aspects of cluster radio halos; e.g. a steep correlation between radio power and X-ray temperature, apparent correlations between plasma temperature maps and radio halos and $0.1-1\mu$ G cluster magnetic fields estimated by the minimum energy argument. Furthermore, the mechanism predicts $10\mu$ G fields along a cold front in A3667. We show several mechanism predictions on the nature of cluster magnetic fields using X-ray observational results of cluster thermal plasmas and new observational methods for measuring the non-Maxwellian nature of the electron velocity distribution function.

### Notes:

Submitted by Nobuhiro Okabe [okabe@astr.tohoku.ac.jp]

## 8.15 Dying sources in clusters

*M. Murgia, P.Parma, H.R.deRuiter, K-H.Mack*

**Abstract:**

The hot gas present in clusters, observable in the X-ray band, is fundamental in confining radio sources. This is true in particular for sources in which the energy supply has ceased. In such objects the hot confining gas prevents rapid extinction of the radio emission; thus we may be able to see a source in a phase where it lacks the structures that are commonly interpreted as indicators of continuing activity, for example radio cores, jets or hot-spots. The confined relativistic plasma preferentially loses its high energy electrons through synchrotron and inverse-Compton losses, which results in a steepening of the radio spectrum. If a radio galaxy goes through multiple epochs of activity one might be able to observe fossil radio plasma remaining from earlier activity confined by the hot gas, as well as features associated with a restarting jet or a radio core. Also in this case the fading lobes are expected to have a steep radio spectra. Here we present the results of a VLA study of three ultra-steep spectrum radio galaxies taken from the Westerbork Northern Sky Survey (WENSS) minisurvey galaxy sample. The sample has been obtained identifying radio sources in the WENSS minisurvey region with bright galaxies($mr<16.5$). Each source is located at the center of an X-ray emitting cluster. The high resolution observations at two frequencies indicate that we are witnessing dying radio sources or (in one case) restarting activity.

**Notes:**

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## 8.16 The X-ray emitting cluster surrounding 3C401

*John Stocke (CASA, Colorado), Chris Reynolds (Maryland), Laura Brenneman (Maryland) & Mitch Begelman (JILA, Colorado)*

### Abstract:

We present new Chandra/ACIS-S observations of the moderately rich (Abell class 2) cluster surrounding the distant (z=0.2), luminous Fanaroff & Riley type II radio galaxy 3C401. The extended radio morphology of 3C401 is a "fat double", with the brightest portions of the source being the core and a luminous jet in the southern lobe. While the core of the source is detected by Chandra, the X-ray emission is dominated by extended emission from the surrounding cluster. This extended emission exhibits substantial clumpiness in the form of "holes" similar to those seen in the clusters surrounding Perseus A and Hydra A. However, these holes are at larger distances from the radio core and at different position angles than the extended radio emission at 20 cm, similar to the case of PKS 2354−35/Abell 4059. We will address the energetics of this radio galaxy/cluster system to determine if the current radio source is capable of making these holes or if they were created during a previous outburst of 3C401, when it was bigger and more luminous than now.

### Notes:

Submitted by John Stocke [stocke@hyades.colorado.edu]

## 8.17 Radio galaxies in high density environments

*Greg Taylor(NRAO), Andy Fabian, Jeremy Sanders, and Steve Allen (Cambridge)*

### Abstract:

The recent wealth of high resolution, high-sensitivity data from the Chandra X-ray Observatory has revealed many dramatic interactions between the hot cluster gas and the central radio galaxy. In the Perseus cluster we can see what appears to be shocks and ripples produced by a continuous blowing of bubbles by the central radio source, 3C84. The X-ray observations also provide a superior knowledge of the thermal density distribution. This, in combination with Faraday Rotation Measure images from radio observations with the Very Large Array gives us some indication of cluster field strengths and topologies. We present radio and X-ray observations for a sample of bright radio galaxies embedded in luminous X-ray cluster including the Perseus cluster.

### Notes:

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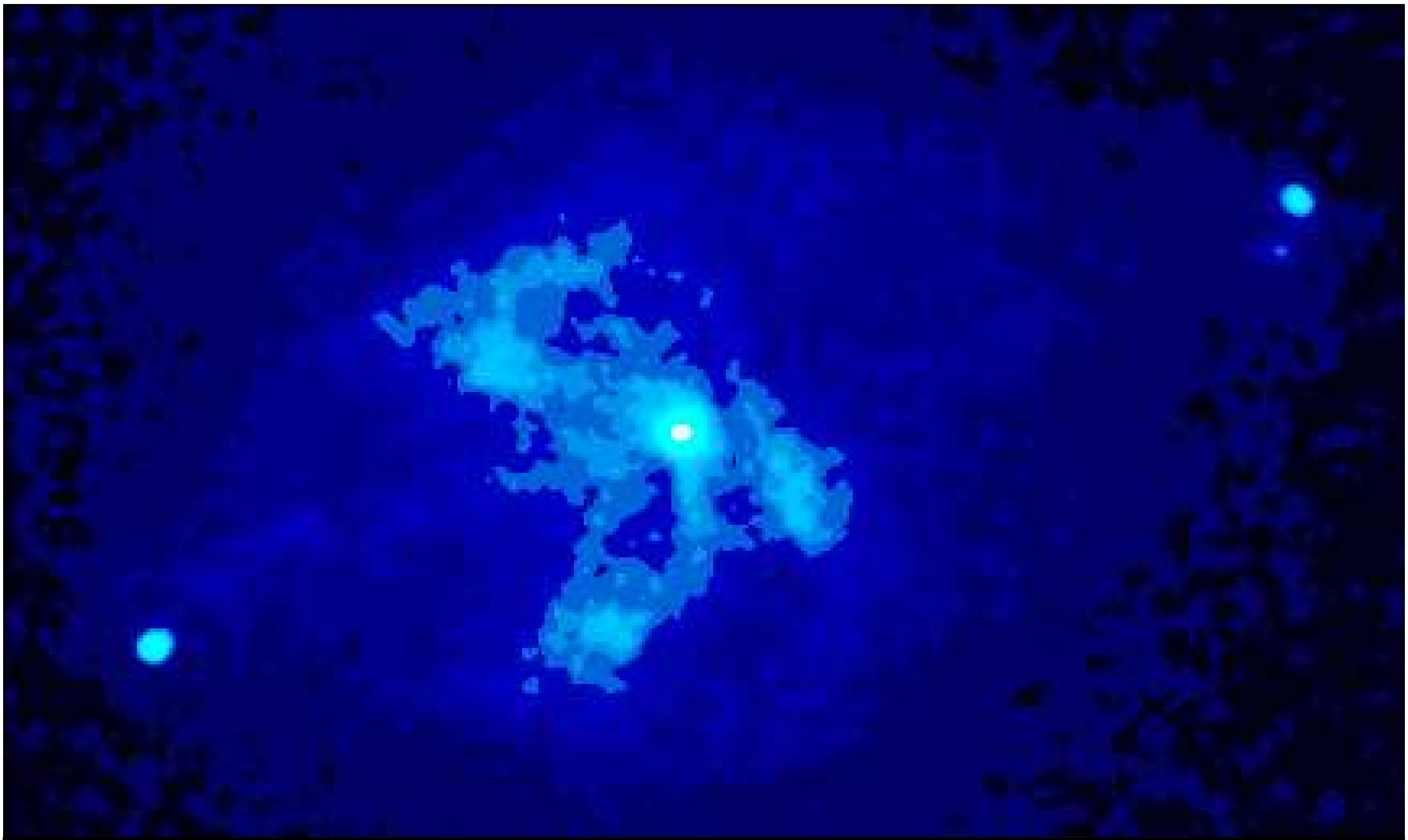

Cygnus A at X–ray (top) and radio (bottom) wavelengths