Scientific Report of the Group of A. Zensus

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Active Galactic Nuclei, Compact Radio Sources and Very Long Baseline Interferometry

1 Introduction and summary

The principal focus of our group’s research continues to be on the parsec and sub-parsec scale radio sources associated with various classes of Active Galactic Nuclei (AGN) and increasingly also on galactic “superluminal” sources associated with X-ray binary systems. The main types of AGN being investigated are associated with highly luminous blazars, quasars and radio galaxies, as well as with the much less luminous Seyfert galaxies and “normal” elliptical galaxies. Of special interest is the intrinsically very weak radio source Sgr A* which coincides with the dynamical center of our galaxy. The luminosity in this sequence of objects ranges over more than 10 orders of magnitude, with the maximum reaching about $10^{46}$ erg/s.

The large body of observational evidence available at present provides a substantial basis for building a comprehensive paradigm that explains the nature of the non-thermal emission from AGN covering the entire electromagnetic spectrum. The essential four elements of this paradigm are: 1) the “prime mover”: a central spinning black hole, 2) the inflow (or accretion) of material through a disk or a torus onto the hole, 3) a “wind” derived from the disk and 4) a collimated outflow or “jet” originating in the region near the black hole. All four elements interact with each other to various degrees and in this way generate the diverse types of “nuclear activity” we observe. There is no comprehensive theory, however, which could describe all the variants in this complex interplay of processes near the black hole and its effect on the transport of mass, angular momentum, and energy.

The evidence from VLB and local radio interferometry, at spatial resolutions ranging from sub-parsec to megaparsec, leaves no doubt that relativistic jets provide the most efficient mechanism for mass, momentum and energy transport, and energize the elongated compact and extended extragalactic radio sources. VLBI allows us to directly image parsec-to-sub-parsec scale regions in or around the jets, significantly closer to their origin than it is possible in any other spectral domain. As such this work is of direct relevance to comparison with the emerging results from the optical and high-energy studies. Some basic questions concerning the physics of nuclear regions of galaxies to be answered by observation and theory include the following:

- What is the working substance or the carrier of energy in the jets? Is it the Poynting flux, pair plasma, ion plasma or a combination of these? There is no definite answer yet to this very basic and seemingly simple question.

- Where and how do jets form? How do they get collimated? They are most certainly related to accretion flows. The favored launch and collimation mechanism is of hydromagnetic nature.

- What is the velocity of jets? The most powerful jets are probably ultra-relativistic (with Lorentz factors of $\geq 10$), whereas jets in Seyfert galaxies are not. But speed measurements in relativistic jets are challenged by the difficulty to distinguish between pattern and bulk flow speed. Significant acceleration or deceleration can also take place along the jet.

- What is the true spatial structure of jets? This question is particularly non-trivial for relativistically beamed outflows in which the observed intensity distribution does not mirror
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exactly the real structure of the jets.

- What is the origin of the distinct enhanced emission “components” observed in the jets? It is generally thought that they are created by stationary or traveling shock waves in the jet; however, some of them may be just traveling patterns.

- Can all of the radio emission from the jets be described by incoherent radiation from relativistic electrons? One consequence of this is that the brightness temperature in the rest-frame of the emitting plasma, cannot significantly exceed $\sim 10^{12}$ K, because of the resulting catastrophic Inverse-Compton cooling.

- What causes the “intraday variability” (IDV) of blazars? To what extent is the IDV of intrinsic or extrinsic (i.e. scintillations) nature?

- How are the radio properties related to those in other spectral domains? For example: many “superluminals” are gamma-ray sources and intraday variability is observable across the electromagnetic spectrum.

- To what extent is the orientation of the jets (through relativistic beaming and Doppler boosting or obscuration by dust tori) and their interaction with the galactic environment responsible for generating the certain observed types and classes of AGN.

- To what extent are low-luminosity AGN such as Seyfert nuclei, scaled-down versions of their high power relatives represented by strong radio galaxies?

Our research projects are primarily based on observations at highest possible angular resolution in the milliarcsecond and submilliarcsecond range using VLBI arrays at centimeter and millimeter wavelengths. Many of these projects make use of the Effelsberg 100-m antenna which is, even at a frequency as high as 86 GHz, one of the most sensitive interferometer elements available. The Mark IV correlator operated by the VLBI group is of great help in performing non-standard VLBI experiments.

Currently, we routinely use VLBI arrays with facility character such as the European VLBI Network (EVN), the VLB Array (VLBA) and global networks for observations at frequencies up to 43 GHz. VLBI imaging at 86 GHz is now possible, but it requires considerable logistic and technical efforts. Measurements at higher frequencies are still in an experimental stage and present a significant challenge for the attempt to overcome the phase-corrupting effects of the atmosphere. However, the results of recent pilot experiments at 129 and 147 GHz are encouraging: for the first time it was possible to detect interference signals at 147 GHz on a transatlantic baseline at an angular resolution of about 20 microarcsecond, the highest achieved so far. Our group is engaged in the effort to advance VLBI imaging at frequencies around 86 GHz, 150 GHz, and 300 GHz with the existing telescopes and several new millimeter wavelength instruments such as ALMA, LMT, and Sardinia Radio Telescope. The group is also actively involved in the development of major future radio astronomical instruments including the Square Kilometer Array (SKA) and space VLBI projects VSOP-2, RadioAstron and ARISE, aiming at maintaining high-resolution interferometry as one of the frontlines of radioastronomy.

A selection of the most important results and highlights from ongoing or completed research projects is presented in this report under the following headings: 2. Radio-bright jets in quasars, blazars and radio galaxies, 3. Active Galactic Nuclei of low radio luminosity, 4. Galactic objects and the local group, 5. Developments in instrumental and observational techniques.
2 Radio-bright jets in quasars, blazars and radio galaxies

2.1 VLBI surveys

86 GHz survey of compact extragalactic sources. A large VLBI survey of compact radio sources at 86 GHz has been started. The first two parts of the survey were completed during the CMVA observing sessions in October 2001 and April 2002, respectively. The third part should be observed in October 2002. A total of 71 different sources has been observed so far (for several objects two observations were made), and fringes have been detected for 93% of the observed sources. The complete survey will increase the total number of objects imaged at 86 GHz by a factor of 3–5 (with a baseline sensitivity of \( \simeq 0.1 \text{Jy} \) and image sensitivity of better than 10 mJy/beam). Such an expanded 86 GHz database will be essential for implementation of the VLBI technique in space and at shorter wavelengths. The survey data will also advance both observational and theoretical studies of extragalactic jets, since it probes the sub–parsec scale regions (Fig ??) of extragalactic jets where radio emission reflects the dynamics and physics of the central engine of AGN. People involved: Lobanov, Krichbaum, Graham, Medici, Kraus, Witzel, Zensus. Collaborators: Greve, Grewing (IRAM, Grenoble).

Figure 1: Morphology of the inner jets in 1749+096, 2145+067 and 3C454.3 at 86 GHz. Shaded ellipses represent the FWHM of the restoring beams. Contours are drawn at -1,1,1.5,...,1.5\(^o\) of the lowest contour level listed in each of the images.
**Space and ground VLBI survey of extremely distant quasars.** A ground and space VLBI survey of high redshift quasars has been conducted using the EVN and VSOP. The source list includes 21 quasars with redshifts of \( z > 3 \) and strong enough for space VLBI imaging observations at 1.6 and/or 5 GHz frequencies. To date, about 50\% of the survey data has been analyzed. The main objectives of the survey are to study the frequency dependent properties of quasars on cosmological scales and to provide data for cosmological tests using the “angular size – redshift” and “proper motion – redshift” dependencies.

Sub-milliarcsecond resolution VSOP images of the extremely distant quasar 1351–018 \((z = 3.707)\) were made at two epochs. The high angular resolution of VSOP at 5 GHz allowed a jet component to be identified within 1 mas of the quasar core. The position of this component changed by 0.5±0.2 mas over a period of less than 3 years, implying a proper motion of 0.18±0.07 mas/year corresponding to a linear speed of \((9.2±3.6)h^{-1}c\) (with the Hubble constant \( H_0 = 100h \) km s\(^{-1}\) Mpc\(^{-1}\) and deceleration parameter \( q_0 = 0.5 \)). Detections of apparent superluminal motions at such high redshifts are relatively rare, which makes this source an important addition to the data base that may eventually constrain the cosmological model using the “apparent proper motion–redshift” dependence.

The high redshift quasar PKS 2215+020 \((z = 3.57)\) has been observed with VSOP at 1.6 GHz. The \(\sim1\) milliarcsecond resolution image of the quasar (Fig. ??) reveals a prominent ‘core-jet’ structure on linear scales from 5\(h^{-1}\) to 300\(h^{-1}\) pc. The brightness temperatures and sizes of bright features identified in the jet are consistent with emission from relativistic shocks dominated by adiabatic energy losses. The jet is powered by the central black hole with estimated mass of \(\sim4\times10^9 M_\odot\). Comparisons with VLA and ROSAT observations indicate a possible presence of an extended radio/X-ray halo surrounding 2215+020. **People involved:** Lobanov. **Collaborators:** Gurvits, Schilizzi (JIVE, Dwingeloo), Frey, Gabányi (FOMI, Budapest), Kawaguchi (NAO, Tokyo).

![Figure 2: VSOP image of PKS 2215+020. The restoring beam is 4.5×1.1 mas. The peak brightness is 221.4 mJy/beam; the contour levels are drawn at -1.0, 1.0, 1.41, 2.82, 4,... of the lowest contour level of 1.2 mJy/beam.](image1)

![Figure 3: ROSAT HRi image of PKS 2215+020 (contours) overlaid on the VLA image (grey scale). The contour levels are drawn at 10, 20, 40, and 80% of the peak of the X–ray emission.](image2)
Kinematics of parsec-scale structures in AGN: the 2 cm VLBA Survey. High resolution radio observations are the most direct method to study the formation and evolution of the radio jets associated with accretion onto massive black holes. An imaging survey at 15 GHz ($\lambda=2$ cm) has been carried out with the VLBA since 1994, aimed at understanding the nature of relativistic flow and the origin and propagation of relativistic jets. Of particular importance is how blazars differ from other quasars and AGN. The high resolution radio images (more than 1000 have been made so far) often show pronounced bends and twists. An overview of the images can be seen at http://www.cv.nrao.edu/2cmsurvey.

People involved: Ros, Zensus, Kadler. Collaborators: Kellermann, Lister, Homan (NRAO, CV), Cohen (Caltech, Pasadena), Vermeulen (ASTRON, Dwingeloo).

![Figure 4: Angular separation $r$ versus time for the main components of selected radio sources from the 2cm Survey. The lines show a least-squares fit to component positions. This plot shows the time sampling and the quality of the kinematical results from the survey.](image)

2.2 Detailed investigations of selected objects

Double helix inside the jet in 3C273. Space VLBI observations of the quasar 3C273 made using the VSOP mission have yielded an image in which the emission across the jet is resolved, revealing two thread-like patterns which form a double helix inside the jet (Fig. ??). This structure is consistent with a Kelvin-Helmholtz instability, and at least 5 different instability modes can be identified and modeled by a light jet with Lorentz factor of 2 and Mach number of 3.5. The model reproduces in detail the internal structure of the jet on scales of up to 30 milliarcseconds ($\sim$ 300 parsecs), and is consistent with the general morphology of the jet on scales of up to 1 kiloparsec.

People involved: Lobanov, Zensus.

The superluminal jet of the quasar 3C 345 at highest resolution. Superluminal motions of jet components along curved trajectories have been observed in the quasar 3C 345 for the last 20 years even on the scales of $\leq$1 mas. To date, 11 jet components have been identified, moving at speeds of $2-20$ c and ejected at different position angles. New images of 3C 345 (Fig. ??) obtained with VSOP at 5 GHz (4 epochs) and at 1.6 GHz (4 epochs), the VLBA at 43 GHz (9 epochs) and 22 GHz (7 epochs), and the CMVA at 86 GHz (4 epochs) emphasize the complexity of the compact jet. The observed component trajectories (Fig. ??) show that while each jet feature follows a unique path, there is still a common trend shared by all of them. Changes of the component ejection angle indicate a periodicity of 8–10 years (Fig. ??), implying an underlying periodic process (e.g. orbital motion and precession in a supermassive binary black hole). Evolution of the component kinematics and flux densities imply a re-acceleration of the jet plasma. Spectral index studies reveal a connection between jet components and optically thick regions at core distances smaller than 1 mas.

People involved: Klare, Zensus, Lobanov, Ros, Krichbaum, Witzel.
Figure 5: VSOP image of 3C273 at 5 GHz. The restoring beam is $2.1 \times 0.5$ mas, oriented at P.A. = $12.9^\circ$. The peak brightness in the image is 4.52 Jy/beam, and the noise level is $\sigma = 2.1$ mJy/beam. The dot-dashed white lines denote the locations of the 4 flux density profiles shown in the inset. A total of 240 such profiles have been measured along the jet. Each of these profiles is centered on the smoothed ridge line (the dashed black line), and oriented orthogonally to it, and has been fitted by two Gaussian components designated P1 and P2. The locations of the peaks of P1 and P2 are marked in the image by the red and blue lines. The double helical pattern formed by P1 and P2 suggests that they result from Kelvin-Helmholtz instability developing in the jet.

**Binary black hole model for AGN.** A hypothesis has been proposed that most AGN contain supermassive binary black hole (BBH) systems, in which the orbital motion and precession are responsible for the observed broad-band emission variations, as well as for the morphological and kinematic properties of radio emission on parsec scales. This scenario explains the variations of radio and optical emission and reproduces the structural changes observed in the parsec-scale jet of the quasar 3C 345 (Fig. ??). It is remarkable that reproducing both the observed light curves (panels A and B of Fig. ??) and trajectory (panel C) of the moving jet feature C7 would require neither a compressed magnetic field, nor helical geometry induced by Kelvin-Helmholtz instability. This implies that the BBH model constitutes a novel paradigm explaining the observed properties of compact relativistic jets. The main factors governing the observed behavior of the jet are then the orbital motion in the BBH system and the precession of the accretion disk, while the jet itself can in principle remain a quasi-stationary and homogeneous outflow on spatial scales of up to $\sim 50$ pc. In this case, even the observed morphology of the compact jet can be reconstructed from the BBH model (panel D), assuming that the radio emitting plasma moves along the magnetic field lines and has a slowly decaying comoving emissivity along the beam.

*People involved: Lobanov. Collaborators: Roland (IAP, Paris).*
A binary black hole in PKS 0420-014? The optically violent variable (OVV) flat-spectrum radio quasar PKS 0420–014 was observed with 3.6 cm VLBI at 9 epochs over a period of three years (1989.32–1992.48). Individual components trace the jet evolution and variability. Superluminal motion with $\beta_{\text{app}} \sim 2–14c$ for five jet components has been found. Components ejected more recently seem to separate faster from the core; all components follow one common curved path within the jet. The ejection of several jet components can be linked to flares in the cm-wave light curves; the most recently ejected component appeared shortly before a simultaneous radio/optical/gamma-ray flare. These results are in agreement with the predictions of the lighthouse model of Camenzind, which explains the observed optical flaring. Alternatively, a precessing binary black hole model can explain both the flux-density variations and the motions of jet components on helical trajectories. The characteristics of the parsec-scale jet in PKS 0420–14 derived from the VLBI observations and the optical light curve of this quasar over the time span 3 Sep 1989 – 7 Dec 1993 were used to determine the characteristics of the binary black hole system. Binary black hole systems may be present in all galactic and extragalactic radio sources with jets. Extragalactic binary systems are the results of mergers and provide a natural explanation why only a small fraction of quasars are radio sources and why extragalactic radio sources are associated with elliptical galaxies. People involved: Britzen, Witzel, Krichbaum, Beckert. Collaborators: Roland (IAP, Paris), Campbell (JIVE, Dwingeloo), Wagner (LSW, Heidelberg), Muxlow (NRAL, Jodrell Bank), Matveyenko (SRI, Moscow).
2.3 Emission models

**Broad-band distributions of brightness temperature in compact, extragalactic jets.** The observed broad-band distribution of brightness temperatures is analyzed, using a large sample of compact extragalactic radio jets. Statistical models are being developed to describe the observed distribution, and to test physical models proposed for explaining the nature of the inner jets in AGN. Multi-frequency VLBI data for the components (mostly cores) of more than 600 sources have been collected from the literature. These samples will be used for modeling the distribution of the observed brightness temperature at several frequencies, and probing different spatial scales in the jets using the frequency dependence of the core position.

The models developed describe the distribution of the observed brightness temperature in terms of the distribution of the intrinsic brightness temperature ($T_0$) and the jet Lorentz factor ($\Gamma_j$), assuming the jets are randomly oriented with respect to the line of sight and are straight within the spatial scale probed by the observation. Three possible distributions are considered: Gaussian, power law and a single value distribution (where $T_0$ and $\Gamma_j$ have the same value in all the sources). Fig. ?? shows the application of the model to the VLBA pre-launch survey using the single value distribution.  

*People involved: Medici, Lobanov.*
Circular Polarization from Relativistic Jets. The measurement of circular polarization in continuum radio emission from the galactic center and compact components of powerful jets at frequencies of a few GHz reveals information about ‘invisible’ low-energy particles in jets. The possibility of explaining the high level of circular polarization by intrinsic mode conversion in the relativistic plasma has been explored. It is found that a substantial part of the electron population is not seen in the direct radiation but is required by the measured linear and circular polarization. The stability of the sign of CP and the variability of both polarizations carries information on the magnetic field structure in these jets and on jet formation mechanisms. People involved: Beckert, Falcke.

2.4 Radio galaxies and CSOs

Subluminal motion in the counter-jet of Cygnus A. Cygnus A is one of the strongest objects detected in the radio domain. It is the closest ($z = 0.057$) strong FR II radio galaxy and therefore a key object for detailed studies of FR II nuclei. In the radio bands, Cygnus A exhibits two strong lobes separated by $\sim 2'$ in the sky, and two highly collimated jets connecting the lobes with the core. Due to the large viewing of the jet with respect to the observer and correspondingly reduced relativistic effects, Cygnus A is an ideal candidate for detailed studies of its jet physics, which is thought to be similar to that in the more beamed quasars.

Recent EVN and VLBA observations of the core reveal a pronounced two-sided jet structure (Fig ??). The kinematics of the jet and counter-jet have been derived from 5 GHz observations at 4 epochs: 1986, 1991 (published by Carilli et al.), 1996 and 2002. On the jet side and on mas scales the jet seems to accelerate from $\beta_{\text{app}} \approx 0.1 - 0.2$ at core separations near 1 mas to $\beta_{\text{app}} \approx 0.4 - 0.6$ at $r \geq 4$ mas ($H_0 = 100\,\text{km}\,\text{s}^{-1}\,\text{Mpc}^{-1}$, $q_0 = 0.5$). Significant structural variability on the counter-jet side is seen for the first time, for which a motion of $\beta_{\text{app}} = 0.35 \pm 0.2$ at $r = 9.5$ mas is derived. The ratio of the flux densities of the jet and counter-jet and the apparent velocity of the jet allow an inclination of the jet axis with respect to the observer of $80 \pm 8^\circ$ to be derived. The flat spectrum of the inner region of the counter-jet (free-free absorption) and the frequency dependence of the jet to counter-jet ratio provide strong evidence for an obscuring torus in front of the counter-jet (Fig. ??).

Internal structure and dynamics of the large-scale jet in M87. The internal structure and dynamics of the radio and optical jet in M87 have been studied and modeled by Kelvin–Helmholtz (K–H) instability developing in a relativistically moving plasma. Analysis of VLA and HST images of M87 indicates the presence of two thread-like features inside the jet, which can be best attributed to the presence of the elliptical surface mode of K–H instability (Fig. ??). Up to knot “A” the jet remains stable against perturbations by the helical surface mode of K–H instability. After knot A the long wave helical surface mode becomes prominent, which leads to oscillations of the flow direction and rapid disruption of the flow. Modeling the jet structure constrains the instability pattern speed, $\beta_w = 0.5 \, c$ and jet viewing angle $\mu_j = 40^\circ \pm 1$. The jet bulk speed can then be estimated from the average observed apparent speed $\beta_{j,\text{app}} = 2.3$. The model explains well the observed morphology and internal structure of the jet on scales of up to $\sim 50''$ (taking into account the apparent jet curvature), which corresponds to linear scales of $\sim 4.7\,\text{Mpc}$. The model is also consistent with the variations of the apparent speed observed in the jet. People involved: Lobanov. Collaborators: Eilek (NMIMT, Socorro), Hardee (U. Alabama, Tuscaloosa).

1245+676: evidence for recurring radio-activity in a radio galaxy. The radio galaxy 1245+676 has an FR II morphology with a total linear extent of $970\,h^{-1}\,\text{kpc}$. Two, largely diffuse, lobes straddle an unusually bright central component. The spectra of the lobes are steep, while the central component has an overall GHz-Peaked Spectrum (GPS).

A series of multi-frequency, multi-epoch VLBI images of the central component have been made, and show a structure unlike any other central component of a double-lobed radio galaxy, which at parsec scales are either point sources or contain a bright core and a one-sided or symmetric radio jets. The central component is similar to the Compact Symmetric Objects; it extends $9.6 \, h^{-1}\,\text{pc}$ and shows two opposing mini-lobes, with similar steep ($\alpha \sim -1.1$) spectral indices, and hot spots, more pronounced in the higher frequency images, embedded in them. The most inverted spectrum area is located close to the center of symmetry of the two mini-lobes; this is interpreted as the location of the core, which is weak as in other CSOs. This series of VLBI images allows an expansion velocity of $v_{\exp} = 0.164 \pm 0.008h^{-1}\,c$ to be measured between the two hot spots which, interpreted as the velocity of the lobes, leads to an estimated age for the central component of $\sim 191$ years.
Figure 10: Top: Kiloparsec–scale jet in M87, with the ridge line and positions of the helical threads inside the jet. Labels mark the “canonical” emission regions identified in the jet. Bottom: Kelvin–Helmholtz instability model for the jet in M87. The jet structure is reproduced by a combination of helical surface (red line, marking the “spine” of the jet) and elliptical surface mode (green lines, marking the locations of the density enhancements inside the jet). The green lines represent a double wavelength fit to the internal structure. In the model curves the two loops lying outside the top border of the image correspond to locations where the jet flow is oriented at a large (> 60°) angle to the line of sight, which leads to a significant Doppler de–boosting of the observed brightness.

Figure 11: 1245+676: The 1.4 GHz image from WSRT (left) shows the whole 970kpc extent of the galaxy. The 5 GHz VLBA image (right) shows that the central component has a CSO morphology. No low-level emission connecting the mini-lobes with the outer lobes is found and 1245+676 is interpreted as an example of recurring radio activity in a galaxy. In this case, the radio activity responsible for the outer lobes has temporarily stopped and while the outer lobes will take an estimated few times $10^7$ years to fade away, radio activity has started again (some $10^2$-$10^3$ years ago) producing the inner, CSO-like structure detected with VLBI. **People involved:** Polatidis, Owsianik. **Collaborators:** Marecki (Toran), Marcha (CAAUL, Lisbon), Bondi (IRA, Bologna), Barthel (Kapteyn, Groningen).
2.5 Intraday variability

**Annual modulation in the variability properties of the IDV source 0917+624**

There is still debate about the origin of short term radio variations in total and polarized flux associated with powerful central engines in Active Galactic Nuclei (AGN). Such variations on time scales of hours to days (Intra-Day Variability, IDV) are common in a subclass of these objects (flat-spectrum Quasars and BL Lacs) and reveal the tiny dimensions of the emitting region. The cause of the variations seen in these sources is currently controversial with claims being made for either: 1) a source-intrinsic origin or 2) an extrinsic origin due to scattering in the nearby (∼100 pc) interstellar medium (ISM). Since the observed extragalactic objects are extremely compact, refractive interstellar scintillation (RISS) must play an important role in the cm-radio regime.

New support for the extrinsic explanation comes from the time scales of the observed variations; there is new evidence which identifies seasonal changes in the variability time scale with refractive interstellar scintillation effects. Such a RISS model takes the annual change of the Earth velocity relative to the scattering screen into account. In September 1998 a remarkable prolongation of the variability time scale in the IDV source 0917+624 was found, with only small variations in flux density during a period of 5 days. This was explained as a seasonal effect, in which the velocity vector of the Earth and the interstellar medium nearly canceled (see Fig. ??). In order to further investigate the applicability of the model for 0917+624, an Effelsberg 6cm-flux monitoring program was performed over the course of one year. Since September 2000 the source appears to have been remarkably inactive and as yet (August 2002), no return to its normal, faster and stronger variability pattern has been observed (see Fig. ??).

Two possible scenarios are suggested to explain the anomalous behavior of 0917+624: Firstly, the interstellar medium is far more complex than presently thought and a change in the scattering properties of the screen might explain the change of the variability mode in 0917+624. Secondly, an alternative interpretation could be based on intrinsic variations in the VLBI structure of the source between 1998 and 2000. The dominant components, which in the past were responsible for RISS, either disappeared or increased their intrinsic size,
Figure 13: Comparison of two periods with different variability pattern: the left curve shows 0917+624 in June 1993 with its normal, strong variability pattern. On the right, a more recent light curve from March 2001 (plotted on the same scale) is displayed. Note the low variations compared to the past.

Figure 14: 15 GHz VLBI maps of 0917+62 at epochs 1999.88 (left) 2000.18 (center) and 2000.91 (right). The easternmost component has an inverted spectrum and presumably is the ‘core’. The component ~ 0.4 mas north-west, separates from the core at a rate of ~ 0.17 mas/yr, or 5.8 c. It was ejected around 1998.6, just before the time when the IDV of 0917+62 stopped for the first time.

hence producing only quenched scattering. Multi-epoch VLBI observations during 1999 and 2000 reveal such structural expansion in the inner region which can explain the slow down in September 1998 (see Fig. ??). It is therefore very tempting to assume that the present quiescence in the variability of 0917+624 is caused by the ejection of a new jet component which should become visible in future VLBI observations. People involved: Fuhrmann, Krichbaum, Cimó, Beckert, Kraus, Witzel, Zensus. Collaborators: Qian(BAO, Beijing), Rickett(U. California, San Diego)

Search for the scattering screen in front of intraday variable radio cores. Refractive interstellar scintillation (RISS) must play an important role in intraday variability (IDV), even if there are source-intrinsic causes, since the source sizes involved are smaller than the scattering size set by the interstellar medium. A new observational approach has been started, in order to directly detect the scattering screen in the foreground of intraday variables. The presence of a scattering screen in the Galaxy responsible for RISS was suggested many years ago. Until now, only indirect hints exist and no attempt has been made to directly detect such a medium in front of IDV sources. A direct detection via line observations would help to identify RISS with the location of particular features in the local ISM (LISM) and, in addition, physical parameters deduced from such observations would give new input for the model of interstellar scintillation. RISS of extragalactic radio sources on timescales of about 1 day requires free, turbulent electrons (in a layer of a few 10s of parsec thickness) at a relatively nearby position (within a radius of ~ 150 pc of the sun) between us and the source.
The ISM surrounding the solar system within a few hundred parsecs is known to contain several major features in the form of clouds, bubbles, supernova shells, star forming regions and molecular as well as HI clouds. Thus, it is quite plausible to imagine such inhomogeneous clouds or shells at this distance with the required amount of ionized material and clumpiness for the RISS screen. First spectral line observations towards IDVs were made in May 2002 in order to search for the nearby screen and resulted in the detection of the CO(2-1)-line at 230 GHz: Figure ?? shows the discovery of a CO-cloud in front of the IDV source 0954+658. The distance to the cloud is probably about 100 pc and fits nicely with theoretical expectations. Such High Latitude Clouds (HLCs) are expected to be surrounded by an envelope of ionized material acting as a shield against the interstellar radiation field. Further line observations of ionized material (e.g. HCO+ or radio recombination lines) are necessary to identify the scattering screen at the position of 0954+658 and are in progress using the Effelsberg 100 m telescope. People involved: Fuhrmann, Cimó, Krichbaum, Beckert, Kraus, Witzel, Zensus.

**Figure 15:** The first detection of a CO cloud in front of an IDV source. Left map: the cloud is located east of 0954+658 and extends in the north-south direction with a minimum extension of 440". The position of 0954+658 is marked with a cross. The IDV source is located behind the outer CO-shell of the cloud, where ionized material producing RISS can be expected. Right panel: Spectrum at the position of 0954+658.

**Statistical analysis of intraday variable sources.** A statistical investigation of IDV characteristics has been made for a sample of sources. A comparison of recent measurements (March 2000) with previous data shows that some sources have changed their characteristics. About one third of the sources in a complete sample showed intraday variations, consistent with previous analyses (Heeschen et al. 1987, Quirrenbach et al. 1992). No correlation between variations and $b_{\text{HI}}$ has been observed at any epoch, and no dependence of variability amplitude on the source flux density is seen. One might expect some dependence on redshift (considered as compactness indicator) or differences in amplitude and/or timescale between BL Lacs and quasars, but no evidence for such correlations came from the analysis.

Scattering theory predicts two regimes of refractive interstellar scintillation: weak and strong. A change between strong and weak occurs around 3–8 GHz (Walker 1998): below a
critical frequency the scattering is strong. This break frequency can be determined by observing variations at different frequencies. However, different patterns have been observed at different epochs, indicating changes in either the source structure or the interstellar medium. In some cases an increase of the variability amplitude at high frequency is seen. This is not in agreement with the expectations from RISS unless one postulates a source-intrinsic and time-variable contribution which increasingly dominates towards higher frequencies. Fig. ?? shows the behavior of different sources in March 2000. In summary: variability can show different characteristics at different epochs due to changes in the apparent source size. Multi-frequency observations constrain the refractive scintillation theory and can be combined with VLBI observations to put constraints on the ISM structure or the intrinsic source sizes.

**People involved:** Cimò, Beckert, Fuhrmann, Krichbaum, Kraus, Witzel, Zensus. **Collaborators:** Wagner (LSW, Heidelberg).

### Quenched scintillation of intraday variable quasars.

Intraday Variability in many extragalactic radio sources is likely to be caused by refractive or weak scattering in the ionized phase of the interstellar medium of our galaxy. From the statistical analysis of variability light curves, correlation time scales and modulation indices can be derived. Together with a theoretical model for scattering in a turbulent medium, properties of the gas responsible for scattering are derived, such as the index of the power spectrum of turbulence and the distance to the scattering medium. With the information on the turbulent medium, the size of the most compact component inside complex sources can be constrained. This new tool has been successfully applied to light curves of the intraday variable quasar 0917+624 and a compact core of only a few tens of μarcsec has been found. The resolution reached with this technique depends on the correlation time in the light curves of the source and is even higher than present day VLBI observations at the relevant wavelength of 2 – 20 cm.

The change of correlation time scales in the course of a year due to changing projected velocity of the observer relative to the interstellar medium opens up the possibility of imaging the source structure beyond the most compact component. The analysis here uses the autocorrelation function of the variable light curve, which depends on the orientation of the projected Earth velocity on the sky and the source structure.

**People involved:** Beckert, Cimò, Fuhrmann, Krichbaum.
2.6 Gravitational lenses

Investigations of 2016+112 using Global VLBI plus Arecibo. The gravitational lens 2016+112 has long been an enigma. The radio structure consists of 2 images of a single background radio source and an arc-shaped region ("C") which VLBI observations have shown to comprise at least 4 components. These are thought to be 2 further, or merging, images of the same background source, but the details of the relationship between them is still unclear. Further global VLBI observations at 1.6 and 5 GHz, together with MERLIN observations, have been made in order to make a detailed spectral study of region C. For both observations the Arecibo telescope was added to the array in order to enhance the detection sensitivity on the long baselines. Preliminary results from the 5 GHz observations indicate that region C is extremely thin (apparently unresolved) in the direction tangential to the separation from the lens. This gives some support to the suggestion that C is in a region of extremely high magnification. People involved: Porcas, Patnaik. Collaborators: Garrett (JIVE, Dwingeloo), Nair (RRI, Bangalore).

![Figure 17: Global 5 GHz map of 2016+112, region C, resolution 1 milliarcsecond.](image)

‘Clumpy’ sub-structure in galaxy lenses. Modeling of 8 GHz VLBA+Effelsberg observations of the gravitational lens system 1422+23 has been performed. In this system it has proved difficult to fit both the observed positions and flux densities of the 4 images using lens models with smooth mass distributions. For this study the position angles of the images were also included as parameters. As it seems likely that sub-structure in the lens mass distribution may affect the image flux densities, N-body simulations of a model galaxy were used to generate synthetic 4-image data sets. Their analysis is being used to study the influence of substructure in the lensing galaxy. People involved: Porcas, Patnaik. Collaborators: Bradac, Schneider et al. (Uni. Bonn).

High sensitivity Global observations of 0218+357. The gravitational lens B0218+357 is thought to consist of a single, isolated gas-rich galaxy, which should be ideal for realistic lens modeling. The background source also varies and a time delay of 10.5 days has been determined, leading to the hope that an accurate value of the Hubble constant can be determined from this system. High resolution and high sensitivity global VLBI observations of the system have been made at 8.4 GHz. The resulting maps of the two images have an rms noise of 30 micro-Jansky/beam, allowing much more of the extended structure of the image jets to be seen. A counter-jet appears to be present in both images. Despite the very low noise levels, no third image or emission from the lens galaxy could be detected. People involved: Porcas, Patnaik. Collaborators: Biggs (JIVE, Dwingeloo), Browne et al. (Jodrell Bank).
3 Active Galactic Nuclei of low radio luminosity

The black hole in the Galactic Center. The Galactic Center is now known to contain the most compelling supermassive black hole candidate, Sgr A*, of about $3 \times 10^6 M_\odot$. The nature of the radio and X-ray emission of Sgr A* was the focus of heated debates in recent years, since it very likely represents the “matter starved” state that most supermassive black holes are presently in. Using a relativistic jet model for Sgr A* the expected synchrotron and synchrotron self-Compton (SSC) emission of such a low-active system has been calculated. The predicted spectrum fits accurately the radio spectrum and the X-ray emission recently detected by Chandra (Fig. 18). In this model the X-ray emission comes from the inner region of a jet close to the black hole. This was subsequently confirmed by Chandra, detecting a huge X-ray flare with rise times of a few minutes only.

![Figure 18: Broad-band spectrum of Sgr A*](image)

Figure 18: Broad-band spectrum of Sgr A*. The hard X-ray points show the detection of Sgr A* with Chandra in the range 2-10 keV. A jet-model spectrum (synchrotron plus synchrotron self-Compton) for a power-law distribution of electrons (PL) and a relativistic Maxwellian distribution (MW) fits the data.

A comprehensive study of the polarization properties of Sgr A* has been made (Fig. 19). Sgr A* does not show detectable linear polarization at a level of 0.1-1% between 1.4 and 112 GHz. However, it exhibits relatively strong and variable circular polarization. The ratio between linear and circular polarization in Sgr A* is the most extreme ever measured for a supermassive black hole. This can be explained by conversion of linear to circular polarization in the relativistic jet.

Recent observations with the BIMA interferometer confirm a linear polarization of about 7% at 230 GHz. The percentage of linear polarization increases more than four-fold from 112 GHz to 230 GHz (Fig. 19, right-hand side). The observations provide evidence for a huge rotation measure of about $5 \times 10^5$ rad m$^{-2}$ – the largest ever measured in any source. The implied depolarizing medium is most likely hot gas accreting onto the black hole. The inferred accretion rate is about $10^{-7} M_\odot$ yr$^{-1}$. This seems to be the first direct evidence for the presence of a hot, optically thin accretion flow around Sgr A*, albeit at a much lower accretion rate than hitherto predicted in the familiar Bondi-Hoyle or ADAF accretion scenarios.

People involved: Falcke, Beckert, Markoff. Collaborators: Bower, Backer, Wright (Berkeley).
**Twin radio jets in NGC 1052; radio and X-ray studies.** The double-sided parsec-scale jet in NGC 1052 was observed with the VLBA at 5, 8.4, 22 and 43 GHz (Fig. 20). These observations have revealed the presence of a dense circum-nuclear absorber obscuring the central engine and covering the bases of jet and counter-jet. The spectral index of the synchrotron emission diverges at both jet cores. In particular, the most compact component of the counter-jet exhibits a spectrum with a spectral index larger than 2.5, ruling out synchrotron self-absorption. Brightness temperature variations along the jet have been determined at all four frequencies, from model fitting the visibility data. They show a frequency-independent cut-off at about 3 milliarcseconds along the approaching jet, implying an absorbing column density of ionized material of $\sim 6 \cdot 10^{22} \text{ cm}^{-2}$. The observed shift of the apparent core position with frequency also confirms the strong influence of free-free absorption in conjunction with steep pressure gradients at the bases of both jets.

Figure 20: The twin jet of NGC 1052 at 5, 8.4, 22 and 43 GHz at epoch 1998.99 observed with the VLBA. Each tick corresponds to 4 milliarcseconds. The gap between both jets (presumably caused by the obscuring torus) becomes smaller at higher frequencies but stays prominent up to 43 GHz. There is no true core detectable, even at the highest frequencies. Component B is totally absorbed at 5 GHz with a spectral index well above 2.5, ruling out synchrotron self-absorption.

Further constraints on the properties of the circumnuclear absorber in NGC 1052 are obtained using the CHANDRA X-ray observatory. A X-ray absorbing column density of $0.8^{+1.5}_{-0.60} \cdot 10^{23} \text{ cm}^{-2}$ is derived from the nuclear X-ray spectrum. This value is in good agreement with the absorbing column density of ionized material towards the approaching VLBI-jet derived from the brightness temperature distribution. Additionally, the CHANDRA data provide for the first time direct evidence for an X-ray jet in NGC 1052 perfectly correlated in extent with the well studied radio jet, which can best be fitted with thermal X-ray emission from a plasma with $kT = 0.5 \text{ keV}$.

Figure 21: VLBA 15 GHz contour images of NGC 1052 at ten epochs shown spaced by their relative time intervals. The contour levels all increase by factors of $3^{1/2}$, starting at 0.58% from the peak of brightness in each epoch, except in 2001.21, where it starts at 0.19%. The common restoring beam is $1.0 \times 0.5 \text{ mas in P.A. 0°}$. 
NGC 1052 has also been studied with a combination of VLBI continuum and spectral line imaging observations and Westerbork Synthesis Radio Telescope spectroscopy. Ten epochs of Very Long Baseline Array (VLBA) data at 15 GHz, spanning almost six years, show bi-symmetric jets, in which multiple sub-parsec scale features display outward motions of typically $v_{\text{app}} \approx 0.26c$ ($H_0 = 65 \text{ km s}^{-1} \text{ Mpc}^{-1}$) on each side. The jets are most likely oriented near the plane of the sky.

HI spectral line VLBI observations reveal atomic gas in front of the approaching as well as the receding jet. There appear to be three velocity systems. Broad, shallow absorption asymmetrically straddles the systemic velocity spanning $-35$ to $85$ km s$^{-1}$. This gas could be local to the AGN environment, or distributed on galactic scales. Superimposed in the range $25$ to $95$ km s$^{-1}$ are several sharper ($3$–$15$ km s$^{-1}$) features, each detectable over a few tenths of a pc at various places along the inner $2$ pc of the approaching jet. The third, deepest system is at “high velocities”, which is receding by $125$ to $200$ km s$^{-1}$ with respect to the systemic velocity of NGC 1052. It may have a continuous velocity gradient across the nucleus of some $10$ km s$^{-1}$ pc$^{-1}$. This atomic gas seems restricted to a shell $1$–$2$ pc away from the core, within which it might be largely ionized.

Westerbork Synthesis Radio Telescope spectroscopy has revealed the $18$ cm OH main lines ($1667$ and $1665$ MHz) in absorption along the full velocity span of $-35$ to $200$ km s$^{-1}$, with their line ratio varying roughly from $1:1$ to $2:1$. They are deepest in the high velocity system, where the OH profiles are similar to HI, suggesting co-location of the atomic and molecular gas, and leaving unclear the connection to the H$_2$O masing gas seen elsewhere. In the high velocity system we have also detected the $18$ cm OH satellite lines: $1612$ MHz in absorption, and $1720$ MHz in emission. The conjugate behavior of the satellite line profiles, and the variable main line ratio resemble the situation in Cen A and NGC 253. People involved: Kadler Ros, Zensus, Lobanov, Falcke. Collaborators: Kerp (U Bonn), Vermeulen, van Langevelde (ASTRON, Dwingeloo), Kellermann (NRAO, Charlottesville), Cohen (Caltech, Pasadena).

**Seyfert 2 galaxies.** Four Seyfert 2 galaxies (NGC 7674, NGC 5506, NGC 2110 and Mrk 1210) have been observed at $18$ cm and $6$ cm with the EVN and MERLIN, providing a large range in angular resolution and surface brightness sensitivity. In the images obtained, jets in these galaxies are complex and there is no one structural form common to them all. NGC 7674 and NGC 2110 have linear or curved double-sided jets. NGC 5506 and Mrk 1210 have multiple components without a clear pattern or axis of symmetry. Although the jets in NGC 7674 and NGC 5506 are weak compared to jets in radio-loud galaxies, mildly-relativistic motion in the range of $0.15c$ to $0.45c$ has been measured, suggesting that the jets are not intrinsically weak but get bent or disrupted. In NGC 5506, the radio emission on small scales ($<10$ pc) is misaligned by $\approx 90^\circ$ with the emission on large scales ($>1$ kpc). People involved: Middelberg, Falcke, Krichbaum, Roy, Witzel. Collaborators: Colbert (JHU, USA), Nagar (OAA, Italy), Norris (ATNF, Australia), Wilson (UMD, USA)

**Seyfert galaxy jet speed distribution.** The bimodality of radio-loudness in active galaxies is probably caused by small-scale properties of the galaxy nucleus. Some candidates for the cause are the black hole mass or spin, the accretion process, the jet formation or mass entrainment, or the density of the surrounding interstellar medium. These various explanations can be classified as “intrinsic” or “environmental”. If the cause is environmental, then one would expect the jets to be initially relativistic and then to decelerate on scales of a few to hundreds of parsecs, whereas if the effect is intrinsic the jets would be launched
slow. Following earlier VLBI imaging observations of Seyfert galaxies with the VLBA in 1996, second- and third-epoch observations have now been made of six objects. These jets have been found to be systematically slower compared to the jets in powerful radio galaxies and quasars. There is no inverse correlation between component speed and distance from the core, and so no evidence that the jets are decelerating as they pass through the NLR; they may, however, be decelerated to sub-relativistic speed within the first parsec or ten parsecs. People involved: Roy, Falcke, Krichbaum, Middelberg. Collaborators: Colbert (Johns Hopkins Univ.), Norris (ATNF), Ulvestad (NRAO), Wilson (U. Maryland & STScI).

Free-free emission & absorption in Seyfert galaxies. The difference between the two main types of Seyfert galaxies is probably due to obscuration of the nucleus by a torus of dense molecular material. The inner edge of the torus is expected to be ionized by optical and ultraviolet emission from the active nucleus and will radiate direct thermal emission (e.g. NGC 1068) and will cause free-free absorption of nuclear radio components viewed through the torus. A search for further examples of thermal emission from the ionized inner edge of the torus or accretion disc has yielded one new candidate (NGC 4388). In NGC 4388 the flat-spectrum radio core was not detected with a deep integration with the VLBA at 8.4 GHz but was detected with MERLIN at 5 GHz, implying a brightness temperature in the range $1.9 \times 10^4$ K to $10^6$ K, which is too low for synchrotron self absorption and may instead be optically-thin thermal emission. Deep integrations with the VLBA at 3.4 cm revealed no evidence for thermal disc-like emission extended perpendicular to the jet or NLR collimation axis in the galaxies T0109-383, NGC 2110, NGC 5252, or Mrk 926.

A sample of eight nearby Seyfert galaxies has been observed at multiple frequencies between 1.4 and 15 GHz with the VLBA to look for a free-free absorption peak due to absorption by a torus. Most of the galaxies observed were found to produce optically-thin synchrotron emission; however a flat or absorbed spectrum in at least one nuclear component was observed in 4 galaxies (NGC 1068, NGC 2639, NGC 5506, Mrk 231, and Mrk 348). Such absorption could in principle be caused by synchrotron self absorption, Razin-Tsytovich effect, or free-free absorption, and the likelihood of each depends individually on the brightness temperature (varying from $10^6$ to $10^9$ K between objects), the presence of water masers (NGC 1068, NGC 2639, and NGC 5506) which indicate an edge-on disc, the presence of large X-ray absorbing columns, and the absence of a counter-jet (Mrk 231 and Mrk 348) which is most easily accounted for by absorption in a nuclear disc. People involved: Roy, Falcke, Krichbaum. Collaborators: Colbert (JHU), Mundell (Liverpool JMU), Norris (ATNF), Ulvestad, Wrobel (NRAO, Socorro), Wilson (U. Maryland & STScI).

The narrow-line region of quasars and Seyfert galaxies. The narrow-line regions (NLRs) of the seven brightest radio-quiet PG (or BQS) quasars ($z<0.5$) have been observed with the Hubble Space Telescope (HST) to image the [OIII] lambda 5007 line emission. It is found that the NLRs are very compact, with typical extents of 2"–4". Two quasars show compact filamentary structures similar to Seyfert NLRs and possibly related to radio outflows. The size of the NLR is found to be proportional to the square root of the [OIII] luminosity (Fig. ??), which is similar to the fundamental scaling found between the size of the broad-line region and continuum luminosity, usually interpreted in terms of a constant photoionization parameter. This relation connects the NLR of radio-quiet quasars and Seyferts over three orders of magnitude in [OIII] luminosity. People involved: Falcke. Collaborators: Bennert, Schulz (U. Bochum), Wilson (U. Maryland & STScI), Wills (U. Texas)
Figure 22: NLR size of AGN versus the emission–line luminosity in [O\textsc{iii}] $\lambda 5007$ (left) and in H$\beta$ (right) on logarithmic scales. The open diamonds are Seyferts, the filled squares are PG quasars. The solid lines show weighted linear fits resulting in $R \propto L_{[\text{O} \text{iii}]}^{0.52}$ (left hand panel) and $R \propto L_{\text{H} \beta}^{0.49}$ (right). This is expected from very simple photoionization models.

4 Galactic objects and the local group

**EVN and MERLIN observations of microquasar candidates.** A systematic search for new microquasars in the Galaxy has been initiated. A cross-identification between X-ray and radio catalogs under very restrictive selection criteria for sources with $|b| < 5^\circ$ has yielded a sample of 13 radio-emitting X-ray sources. Follow-up observations of 6 of these sources with the VLA have provided accurate coordinates, which were used to discover optical counterparts for all of them. These six sources have now been observed with the EVN and MERLIN at 5 GHz. Five of the six objects have been detected and imaged, presenting different morphologies: 1RXS J001442.2+580201 has a two-sided jet, 1RXS J013106.4+612035, 1RXS J072259.5−073131 and 1RXS J072418.3−071508 have one-sided jets, and 1RXS J062148.1+174736 is compact. 1RXS J001442.2+580201 and 1RXS J013106.4+612035 are thus promising microquasar candidates in our Galaxy.

Figure 23: Images of 1RXS J001442.2+580201 using EVN and MERLIN observations. The axis units are in mas. The EVN+MERLIN image was $(u, v)$-tapered with a FWHM at 10 MA.

The persistent microquasar LS 5039 has been studied using the EVN and MERLIN. These observations confirm the presence of an asymmetric two-sided jet reaching up to $\sim 1000$ AU on the longest jet arm. The results suggest well-collimated radio jets, which bend with increasing distance from the core, and/or precession. This persistent source can be used as a laboratory to explore the accretion/ejection processes taking place near compact objects.

*People involved: Ros, Massi. Collaborators: Ribó, Paredes (U. Barcelona), J. Martí (U. Jaén)*
Jet-domination in X-ray binaries. Stellar mass black holes show state changes on very short timescales. The most dramatic one is from the high-soft to the low-hard states, where the X-ray spectrum changes from black-body dominated emission to a pure power-law spectrum. This change may be associated with a change in accretion rate and the disappearance of accretion-disk emission. The JDAF model (jet plus optically thin accretion flow) has been applied to a number of X-ray binaries (see Fig. ??). The model suggests that jets in X-ray binaries (XRBs) produce most of the radio, near-infrared and even the hard X-ray power-law emission in the low-hard state. The radio synchrotron emission associated with these states correlates with the X-ray emission in several sources (Fig. ??). The JDAF model reproduces this correlation simply by changing the power in the jet.

If relativistic jets from X-ray binaries indeed produce X-ray emission, relativistically beamed jets should be present in X-ray binaries (or microquasars). ROSAT and Chandra-observations have discovered several ultra-luminous X-ray sources (ULXs) exceeding luminosities of $5 \times 10^{39}$ erg/s. Are these, in fact, the beamed sources? This hypothesis was investigated with a simple population synthesis model with relativistic beaming for XRBs. The model explains well the log N–log S distribution of X-ray point sources in nearby spiral galaxies. This suggests that many of the ULXs would be the stellar-mass analogues to blazars in the universe, i.e. microblazars.  

People involved: Falcke, Marko®, Körding. Collaborators: Fender (U. Amsterdam), Nowak (MIT), Corbel (Saclay)
Active Galactic Nuclei, Compact Radio Sources and VLBI

VLBI studies of radio supernovae (SN 1993J, SN 1979C, SN 1986J). Evolution of the radio supernova SN 1993J has been monitored in detail, providing excellent data for comprehensive theoretical-observational analysis. The shell-like radio structure of SN 1993J has expanded in general accord with models of shock excited emission, showing almost circular symmetry for over 8 years, except for a bright feature at the south-eastern region of the shell which has been observed at every epoch. The spectrum of SN1993J has flattened from $\alpha \simeq -1$ to $\alpha \simeq -0.67$ ($S_{\nu} \propto \nu^{\alpha}$). The expansion can be modeled well with a single slope but a deceleration, fit with two slopes, is better. There are also intriguing hints of structure in the expansion curve. A comparison of the optical and VLBI results on the details of the deceleration show some discrepancies.

The size of SN 1979C in M100 has been determined from observations at $\lambda 18 \text{ cm}$ made in June 1999 (20 years after explosion) with a sensitive four-antenna VLBI array. Comparison with previous observations shows that the supernova shock was initially in free expansion for 6±2 yrs and then experienced a very strong deceleration. The onset of deceleration took place a few years before the abrupt change in the trend of the integrated radio flux density curves. We estimate a value of $M_{\text{sw}} \sim 1.6 M_\odot$ for the mass swept up by the shock front at the time of the observations. Since the supernova has significantly decelerated, the mass of the hydrogen-rich envelope ejected by the progenitor, $M_{\text{env}}$, should be much less than $M_{\text{sw}}$, thus suggesting that SN 1979C exploded in a binary star system where the companion stripped off a substantial amount of the hydrogen envelope of the supernova.

A single-epoch $\lambda 6 \text{ cm}$ global VLBI observation of SN 1986J made 16 yr after its explosion has revealed a distorted shell of radio emission, indicative of a deformation of the shock front. The angular size of the shell is $\sim 4.7 \text{ mas}$, corresponding to a linear size of $\sim 6.8 \times 10^{17}$ for a distance of 9.6 Mpc to NGC 891. A mild deceleration in the expansion has occurred,

![Figure 27](image1.png)  
![Figure 28](image2.png)

**Figure 27:** Weighted least squares fit to the outer shell radius of SN 1993J as a function of the time since explosion, allowing for a change in its deceleration rate. The VLBI data up to $t \leq t_{\text{br}}=403$ days (where the solid and dashed lines in the figure cross each other) can be well fitted by a power-law with index $m_1=0.933$ (solid line), while for $t \geq t_{\text{br}}$ the best fit is given by power-law of index $m_2=0.827$ (dashed line). The VLBI data for epochs below 180 days are taken from Bartel et al. (Science, 287, 112, 2000). Note the logarithmic scale.

**Figure 28:** Angular diameter vs. age of SN 1979C. B85 indicates the size estimate from Bartel et al. (Nature, 318, 25, 1985) normalized to our model, F99, the size estimated by us based on the optical results of Fesen et al. (AJ, 117, 725, 1999), and M01 indicates our results. The solid line indicates a possible expansion, which is free for the first 5 yrs and decelerated from then on. The size estimate F99 shown is compatible with this expansion scenario and it would be slightly different for scenarios where the free expansion lasts much longer than 5 yr, which is not the case.
compared with previous average speed measurements. An estimate of the mass ejected at explosion of \( \gtrsim 12 \, \text{M}_\odot \) implies that the supernova progenitor must have kept intact most of its hydrogen-rich envelope by the time of explosion, which favors a single, massive star progenitor scenario. Four bright knots delineate the shell structure and there is also a central minimum of emission, which can be tentatively identified with the center of the supernova explosion. If this is the case, SN 1986J has then suffered an asymmetric expansion. This asymmetry may be due to the collision of the supernova ejecta with an anisotropic, clumpy (or filamentary) medium. People involved: Ros. Collaborators: Marcaide, Guirado (U. València), Pérez-Torres, Mantovani, Trigilio (IRA-CNR), Alberdi, Lara (IAA-CSIC), Diamond (Jodrell Bank), Shapiro (Harvard-CfA), Weiler (NRL), Preston (JPL/NASA), Schilizzi (JIVE), Sramek (NRAO) Van Dyk (Caltech), Whitney (Haystack). Weiler (NRL, Washington)

\[ \text{DECLINATION (J2000)} \]

\[ \text{RIGHT ASCENSION (J2000)} \]

A search for very low mass objects around nearby stars. Nearby M dwarfs are best suited for searches for planetary companions. VLBI phase-referencing observations with sensitive telescopes are able to detect radio star flux-densities of tenths of mJy as well as to position the star on the sky with sub-milliarcsecond precision. We have initiated a long-term program, using Effelsberg and the Bonn MKIII and MKIV VLBI correlators in combination with NASA DSN dishes, to revisit the kinematics of nearby, single M dwarfs. The precision of the astrometry allows us to search for possible companions with masses down to 1 Jupiter mass. Analysis is in progress and 3 stars out of 7 could be detected so far. People involved: Alef, Ros. Collaborators: Guirado, Marcaide (U. Valencia), Jones, Preston (JPL, Pasadena)

Towards proper motions in the Local Group. Key, and still largely missing, parameters for measuring the dark matter content and distribution of the Local Group are the proper motion vectors of its member galaxies. The expected proper motions for galaxies within the Local Group, ranging from 20 to 100 \( \mu \text{as/yr} \), are detectable with VLBI using the phase-referencing technique. Hence we conducted phase-referencing observations of bright masers in IC 10 and M33 to measure the relative position of the masers with respect to background quasars. We observed the \( \text{H}_2 \text{O} \) masers in IC 10 three times over a period of two months to check the accuracy of the relative positions. The rms of the relative positions for the three observations is only 10 \( \mu \text{as} \), which is approximately the expected position error due to thermal noise. With this accuracy we expect a 2.5 \( \sigma \) detection of the galaxy proper motion within one year. Further observations of the masers in M33 will also provide a method to measure the geometric distance to M33. This will allow re-calibration of the extragalactic
distance scale based on Cepheids. The method is to measure the relative proper motions of two H$_2$O maser sources on opposite sides of M33. The measured angular rotation rate, coupled with other measurements of the inclination and rotation speed of the galaxy, yields a direct distance measurement. People involved: Brunthaler, Falcke, Henkel. Collaborators: Reid, Greenhill (CfA, Cambridge).

5 Developments in instrumental and observational techniques

5.1 Progress in mm-VLBI

VLBI observations at 2 mm wavelength. Following earlier attempts to detect VLBI fringes at wavelengths shorter than 3 mm, two successful VLBI observations at 2 mm wavelength were made in 2001 and 2002. In April 2001 the two quasars 3C 273 and 3C 279 were detected at $SNR \approx 10$ on the 3100 km baseline between the 30 m telescope on Pico Veleta (Spain) and the 14 m telescope in Metsähovi (Finland). This indicated that at least the brightest known AGN were compact enough for VLBI at wavelengths shorter than 3 mm. A second experiment, performed in April 2002, in which also the 12 m telescope on Kitt Peak, the 10 m Heinrich-Hertz telescope on Mt. Graham and the SEST telescope in Chile participated, resulted in the detection of relatively strong ($SNR \leq 75$) correlated signals on several AGN. With fringe detections on the 8500 km long VLBI baseline between Arizona and Spain a new world record in angular resolution was set ($\sim 20\mu$ as). The strength of the detections and the number of the detected sources indicate that future VLBI at 2 mm or 1 mm is technically possible. In the same observations, VLBI fringes at 129 GHz were successfully detected on SiO line sources, representing the highest frequency spectral line detections to date.

With brightness temperatures of the detected VLBI cores in the range of $T_B \sim 10^{10-11}$ K, future 2 & 1 mm-VLBI experiments will allow the innermost regions of Blazars and other AGN to be imaged with a spatial resolution of a few hundred to thousand Schwarzschild radii (for sources at $z > 0.1$). In the next few years another key target for VLBI at 2 & 1 mm will be the Galactic Center Source Sgr A*. A single detection on a long baseline to
Figure 31: A 86 GHz VLBI map of M87. The data were obtained in October 2001, using the 512 Mbit/s MKIV recording mode. This higher recording rate enhances the sensitivity of the VLBI array. Owing to the relative proximity of the galaxy, the spatial resolution is only 10 light days.

South America (eg. with the participation of SEST, APEX and/or other ALMA proto-type antennas), should allow a direct measurement of its size (and possibly non-uniform brightness distribution) to be made, since mm-VLBI observations are able to look through the blurring scattering screen. The necessary enhancement of the sensitivity of mm-VLBI is on its way and new results can be expected with the phased IRAM Plateau de Bure interferometer becoming operational for mm-VLBI in a few months, and an enhancement of the VLBI recording rate being forseen for 2003 (MK5 recording with up to 1 Gbit/s).


512 Mbit/s observing and a first 86 GHz VLBI map of M87. Following the upgrade of MKIV and VLBA recorders for 512 Mb/s recording during 2001, it seemed timely to use this potential 40% sensitivity increase for mm-VLBI observing. Hitherto, most of the global 3mm-VLBI observations were done at either 112 Mbit/s or 256 Mbit/s. As the VLBA cannot sustain 512 Mb/s for more than a few hours, this test experiment was restricted to Haystack and the 3 European antennas Effelsberg, Pico Veleta and Onsala. Nine AGN were observed in snap-shot mode, with up to 1 hour on source. Although the uv-coverage was only very limited, maps of all sources could be made, reaching noise levels of a few mJy/beam. As an example an 86 GHz image of M 87 is shown in Figure 31. In order to improve the uv-coverage the 512 Mbit/s data were combined with VLBA data taken one day earlier at the normal 256 Mbit/s rate. This is the first 86 GHz VLBI image of this object to show not only the prominent VLBI core ($T_B = 1.5 \cdot 10^{10}$K), but also partially resolved and weak jet emission at an orientation consistent with the jet seen at longer wavelengths (eg. at 43 GHz). Better data and a more uniform uv-coverage will be necessary to further improve the map quality and
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study the jet in more detail. As the minor axis of the observing beam is aligned with the main jet direction (East-West), details as small as 70 μas could be detected, which translates to only 35 Schwarzschild radii, assuming a central super-massive Black Hole of $10^9$ M$_\odot$. Millimeter-VLBI has now reached a sensitivity which allows relatively faint nearby radio galaxies to be imaged with a spatial resolution of a few ten to a few hundred Schwarzschild radii. This will facilitate a very detailed investigation of the kinematics near the active nucleus and from this a better understanding of the production and collimation mechanism of relativistic radio jets. People involved: Krichbaum, Graham, Alef, Kraus, Witzel, Zensus. Collaborators: Greve, Grewing, (IRAM), Attridge, Phillips, Rogers, Titus, Whitney (MIT-Haystack), Conway, Booth (Onsala).

5.2 Phase-referencing and phase-correction techniques

Space-VLBI phase-reference investigations. The close pair of compact radio sources, 1308+326 and 1308+328, were observed with the VSOP program. Observations were made at 6 cm using the VLBA and HALCA. For this close pair, both sources are simultaneously within the primary beam of the HALCA telescope; thus, even though HALCA cannot switch pointing rapidly, it was possible to make phase-referenced observations, using the very compact 1308+328 as a phase-reference for 1308+326. It proved possible to make the first ever space-VLBI phase-reference map of a radio source, 1308+326. Analysis of the phase-reference residuals permitted an estimate of the typical position error of HALCA to be made. This proved to be around 2 to 5 m, much better than the 80 m mission requirement. Further observations of this pair at 18 cm have been made, and analysis of this data set is continuing. The ionosphere above the ground radio telescopes makes a very significant contribution to the relative phase on baselines to HALCA.

The feasibility of phase-referencing with space VLBI has also been demonstrated with 5 GHz VSOP observations of the quasar pair B1342+662/B1342+663. From the residual phases, an upper limit of 10 meters was derived for the uncertainty of the HALCA position error. People involved: Porcas, Ros. Collaborators: Rioja (OAN, Alcala), Guirado, Marcaide (U. Valencia), Jones, Preston (JPL, Pasadena), Lestrade (CNRS, Meudon), Pérez-Torres (IRA, Bologna).
Cluster-cluster mode VLBI investigations. VLBI observations of 4 sources were made SIMULTANEOUSLY at 18 cm using the cluster-cluster concept in 1999. The array comprised 4 antennas of the VLA, 4 sub-clusters of the WSRT array and 3 antennas from Jodrell Bank and MERLIN. Multi-channel (and multi-tape) MK3 recording was used to record the 4 sources in 4 “parallel interferometer arrays” (the MK2 telescope at Jodrell was switched rapidly to provide the 4th channel there). The complicated correlation of the data was performed using the MPIfR MK3 correlator during its last days of operation in 2000. Fringes were successfully found on all 4 sources in all sub-channels of all antennas. Analysis of the data is continuing. The 4 sources are very close to each other on the sky; the change of the relative phase between the sources provides a powerful means of studying ionospheric phase fluctuations on small angular scales. People involved: Porcas, Alef. Collaborators: Rioja, Desmurs (OAN, Alcala), et al.

Figure 34: Phase of 3C84 (left: separation 1.3 deg) and 0300+470 (right: separation 6.2 deg) w.r.t. 0309+411

Phase-reference mapping at 86 GHz. Although VLBI phase-reference mapping has become a standard tool for imaging weak radio sources, at mm-wavelengths the short temporal and spatial coherence of the troposphere makes the technique unusable in most situations. The VLBA at 86 GHz was used, in dynamic scheduling mode, to explore the limits of phase referencing, using the close source pair 1308+326 and 1308+328, and with rapid switching (scan lengths of 10, 15 or 20 s) between the sources. The stronger of the sources (1308+326) could be detected in essentially all of these short scans, and for some periods it proved possible to unambiguously follow and connect the phase between successive measurements. This permitted the first 86GHz VLBI phase-reference map of a source (1308+328) to be made. Although only about 20% of the source flux appears in this preliminary map, it is hope to improve this with a more careful data analysis. People involved: Porcas. Collaborators: Rioja (OAN, Alcala).

Millimeter-VLBI imaging with fast frequency switching. A new kind of phase referencing for the VLBA has been demonstrated, which enables the sensitivity in mm-VLBI to be increased by an order of magnitude. If a source is observed in short cycles between the target frequency, \( \nu_t \), and a reference frequency, \( \nu_{\text{ref}} \), the \( \nu_t \) data can be calibrated using the \( \nu_{\text{ref}} \) data. The phase transfer has been demonstrated on 3C 279, where an 86 GHz image was made with 90% coherence compared to self-calibration at \( \nu_t \).
The main impacts of fast frequency switching are the ability to image some of the nearest, but relatively weak AGN cores with the high angular resolution of 3mm VLBI and to phase-reference the $\nu_t$ data to the $\nu_{\text{ref}}$ core position, enabling the detection of possible core shifts in jets due to optical depth effects. This ability will yield important constraints on jet properties and might be able to discriminate between the two competing emission models of Blandford-Königl jets and spherical advection-dominated accretion flows (ADAFs) in low-luminosity AGNs. **People involved:** Middelberg, Falcke, Krichbaum, Roy. **Collaborators:** Walker (NRAO, USA)

**Atmospheric phase correction for mm VLBI: water-vapor radiometer.** A scanning 18 to 26 GHz water-vapor radiometer is being built for installation at Effelsberg to provide remote sensing of the atmosphere above the telescope. It is based on a design by Alan Rogers (MIT) and has additionally noise injection, temperature stabilization, and weatherproof enclosure. It measures emission from atmospheric water vapor, from which the atmospheric contribution to VLBI phase and amplitude measurements can be inferred and removed, and should extend coherence times and hence sensitivity. Initial measurements on a room-temperature absorber in a single 1 GHz-wide frequency channel and 0.1 s integration time show instrumental stability of better than 150 mK ($3 \times 10^{-4}$) on a timescale of 1000 s, which corresponds to a coherence of 88 % when the corrections are applied to 86 GHz VLBI phases (Fig ??). The noise should be reduced to the target 50 mK when the full 9 GHz bandwidth frequency-sweep across the line is used, the integration time is extended to 3 s per spectrum, and noise injection is used for gain calibration. Measurements at the zenith in a single channel show that the atmospheric temperature fluctuations are easily seen, being 13 times the instrumental noise level. The radiometer will be moved to the control building roof to operate in parallel with VLBI observations for a period for further tests and will then be moved to the focus cabin roof to look skywards along the optical axis. **People involved:** Roy, Graham, Keller, Krichbaum, Mattes, Tenber. **Collaborators:** Rogers (MIT, Haystack).

**Atmospheric phase correction for mm VLBI: rapid $T_{\text{sys}}$ measurement.** In fine weather, phase correction of 86 GHz VLBI observations can in principle be made based on high-precision $T_{\text{sys}}$ measurements, and a demonstration was made using data from Pico Veleta during a VLBI run. The source BL Lac was observed under clear skies for 8 h on April...
Figure 37: LEFT: Time series of $T_{\text{antenna}}$ with WVR looking at zenith under clear skies at MPIfR in Bonn, showing peak-to-peak fluctuations of 8 K due mostly to fluctuations in the atmospheric water vapor. RIGHT: Time series of $T_{\text{antenna}}$ with the WVR looking at an ambient-temperature absorber, showing peak-to-peak fluctuations of 1 K due mostly to fluctuations in the temperature of the absorber which was exposed to changing wind and sunlight. The instrumental fluctuations are much less than the atmospheric fluctuations, as expected.

18th, 2000 by the CMVA (PV, ON, KP, FD, HC). Tropospheric path lengths were estimated at Pico Veleta every 2 s, derived from $T_{\text{sys}}$ measured at 200 GHz in parallel with the VLBI observation at 86 GHz.

Figure 38: Fringe-rate spectra on the Pico Veleta to Onsala baseline for 6.5 min of data before (left) and after (right) applying tropospheric phase correction at Pico Veleta. The peak flux density is increased from 690 mJy to 1050 mJy by the phase correction. The phase time series that yielded the fringe-rate spectra are inset.

The VLBI data were fringe-fitted with a 6.5 min solution interval; the reduction was repeated with tropospheric path corrections applied to the raw data, allowing a comparison of phase coherence before and after phase correction. The coherence of 11 scans on a 180 s timescale was improved by factors from 1.05 to 1.91, five scans were changed by less than 1.05, and three scans were degraded by factors of 0.84 to 0.72. Thus, the phase correction at Pico Veleta was found to improve the coherence most of the time. The peak flux density in the fringe-rate spectra was usually improved by the correction (Fig. ??), and the peak flux density in the resulting image was increased from 414 mJy beam$^{-1}$ to 504 mJy beam$^{-1}$. However, this technique works only under clear skies, where the atmospheric emission is dominated by water vapor and not by liquid water in clouds. Water-vapor radiometry allows subtraction of the cloud component and is more robust under more typical weather.

People involved: Roy, Krichbaum. Collaborators: Bremer, Greve (IRAM, Grenoble)
5.3 New digital radio telescopes (LOPES/LOFAR/SKA) and astroparticle physics

A number of initiatives are currently investigating new technologies for the next generation of radio telescopes at MHz and GHz frequencies, in particular the Square-Kilometer-Array (SKA). A novel aspect of these next generation radio telescopes is the possibility of digital multi-beamforming, which will make possible investigations of the largely unexplored transient radio sky. The fastest transient signals are produced by cosmic rays. Radio pulses from these air showers were measured during the late 1960s in the frequency range from 2 MHz to 520 MHz, but lack of digital data processing at that time prevented a more thorough study.

In the near future, an ideal instrument for detection of radio emission from cosmic rays will be LOFAR (LOw Frequency ARray) which is envisaged as a next-generation digital instrument working at 10-200 MHz (LOFAR would detect air showers from $>2 \cdot 10^{14}$ eV to $\sim 10^{20}$ eV and possibly beyond). To test the LOFAR technology and demonstrate the ability to detect air showers a “LOFAR Prototype Station” (LOPES) is being built. It will operate jointly with an existing air shower array (KASCADE in Karlsruhe, Fig. ??). LOPES will consist of about 100 fully-digital antennas operating in the frequency range of 40-80 MHz. The project is mainly funded by a grant from the Ministry of Science and Education (BMBF).

The hardware for LOPES (active LOFAR antenna, A/D-board, memory module etc.) is currently being developed with MPIfR help at ASTRON in Dwingeloo. Prototypes of the antenna, A/D-boards, and memory module have been built and are being tested. First RFI (Radio Frequency Interference) measurements have also been performed in Dwingeloo and at KASCADE and it has been demonstrated that digital RFI-suppression can bring the noise down to the Galactic noise limit.

In addition to the experimental verification, work has been done on modelling the physical processes that give rise to pulsed radio-emission from cosmic ray air showers. It has been shown that the emission can be described by coherent geo-synchrotron emission from relativistic electrons and positrons in the shower deflected by the Earth magnetic field. Theoretical pulse spectra and early experimental data are shown in Fig. ??.. The radio detection of cosmic rays promises to be an ideal combination of radio astronomy and (astro-)particle physics, and can also be applied to neutrino searches and to upcoming large cosmic ray arrays such as Auger. **People involved:** Falcke, Horner, Huege. **Collaborators:** Gorham (Hawaii), Kant, de Vos (ASTRON, Dwingeloo), Kampert, Schieler (FZK, Karlsruhe).

![Figure 39](image_url)

**Figure 39:** Left: Picture of the KASCADE air shower array where the LOFAR Prototype Station LOPES will be installed. Right: Theoretical spectra of a radio pulse from a $10^{17}$ eV air shower in different geometrical configurations of the shower front in comparison with experimental results and theoretical estimates.