AGN Jets in a Nutshell
(Review)

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The radio emission observed from the relativistic jet outflows emerging from the central regions of Active Galactic Nuclei (AGN) is synchrotron radiation, indicating the presence of both highly relativistic electrons and magnetic fields. Theoretical models for the electromagnetic launching of these jets have long indicated that a helical magnetic (**B**) field component should be generated, through the winding up of an initial longitudinal (poloidal) field component by the rotation of the cental black hole and accretion disk. This helical field component should then propagate outward with the jet plasma.

Polarization VLBI observations provide direct information about the **B**-field structures in the synchrotron-emitting radio jets and the medium through which they propagate. Together with Faraday rotation measurements, it is possible in some cases to reconstruct the three-dimensional magnetic-field structure. There is now plentiful evidence for the presence of helical or toroidal **B** fields associated with the jets of Active Galactic Nuclei on a wide range of scales, but it is also clear that **B** fields generated by local phenomena such as shocks and shear can also be important. Distinguishing between inherent and local **B** fields can be challenging, and the development of diagnostics based on correlations between intensity, linear polarisation, circular polarisation, rotation measure and spectral index information is promising for this purpose.

Striking limb brightening has been observed for essentially all relatively nearby AGN that have been observed with sufficient resolution across the jets. This has sometimes been interpreted in terms of preferential Doppler boosting of a "sheath" of emission, but it seems more likely that such limb brighening is due to some intrinsic property of the jet, which is independent of the viewing angle, such as its helical **B** field, or mass loading and/or particle acceleration at the jet edges.

An extensive analysis of the sub-parsec region of 3C 84

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Jets launched by AGN are essential to comprehend super-massive black holes (SMBH) and their immediate surroundings. The main jet launching scenarios are either due to magnetic field lines anchored to the accretion disk (Blandford & Payne 1982) or directly connected to the black hole's (BH) ergosphere (Blandford & Znajek 1977), and are an ongoing, hot topic of active research.

3C 84 (NGC 1275) is supremely suitable for testing such jet launching mechanisms, as well as studying the innermost, sub-parsec AGN structure and jet origin.

Very long baseline interferometry (VLBI), and specifically at millimeter wavelengths, offers an unparalleled view into the physical processes in action, in the close vicinity of BHs. Utilising such mm-VLBI observations of 3C 84, we study the jet kinematics of the VLBI core of 3C 84 by employing all available, high sensitivity mm-VLBI data sets of this source. As part of this analysis we associate the component ejection events with the variability light-curves at radio frequencies and γ-rays. Furthermore, by cross-correlating these light-curves, we determine the time-lags between them and draw conclusions regarding the location of the high energy emission at the jet base. In this talk I will present our very recent results and offer a comprehensive summary of jet launching in 3C 84.

Probing the presence of an external medium at the jet head of 3C 84 with polarization observations with VLBA at 43 GHz and KVN at 86-141 GHz

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3C 84 is a young radio source located at the center of elliptical galaxy NGC 1275. Recent VLBI observations found that head of its jet, so called C3 region, wobbled around the same position for a few months and propagated again. This implies that C3 is the region where the jet is colliding with an inhomogeneous ambient medium. However, the emission from such ambient medium is so weak that it is difficult to directly confirm its presence. One way to probe the presence of the external medium is to measure the Faraday rotation measure, a phenomenon in which the polarization angle is rotated as a function of frequency by the plasma between the emitter and the observer. We (i) performed the multi-frequency polarization observations of 3C 84 using the Korean VLBI Network (KVN) at 86-141 GHz, and (ii) analyzed the Very Long Baseline Array (VLBA) 43 GHz data. The Faraday rotation of $(3-4)\times 10^5$ rad m^{-2} measured with KVN at 86-141 GHz is consistent with 3×10^5 rad m^{-2} measured within the bandwidth of VLBA at 43 GHz. Such a constant Faraday rotation over a wide frequency range indicates that the origin of the Faraday rotation is external to the jet. We also found that there is no strong correlation between the light curve and the Faraday rotation at C3. These results strongly suggest the existence of external ambient medium interacting with the jet of 3C 84.

Persistent Structure of Magnetic Field in Parsec-scale AGN Jets

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We have analyzed parsec-scale linear polarization properties of 436 active galactic nuclei (AGN) based on 15 GHz polarimetric-sensitive Very Long Baseline Array (VLBA) observations. We present polarization and total intensity images averaged over at least five epochs since 1996 January 19 through 2019 August 4. Stacking improves the image sensitivity and effectively fills out the jet cross-section both in total intensity and linear polarization. It delineates the long-term persistent magnetic field configuration and its regularity by restoring spatial distributions of the electric vector position angle (EVPA) and fractional polarization, respectively. On average, about 10 years of stacking period is needed to reveal the stable and most-complete polarization distribution of a source. We find that the degree of polarization significantly increases down and across the jet towards its edges, typically manifesting U or W-shaped transverse profiles, suggesting a presence of a large-scale helical magnetic field associated with the outflow. In contrast to earlier studies based on smaller samples, we find that quasars and BL Lacs show comparable fractional polarization of their jets. We confirm that the EVPAs in BL Lacs tend to align with the local jet direction, while quasars show no preferential polarization orientation.

Ray-Tracing in Relativistic Jet Simulations

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Many active galactic nuclei produce highly collimated, relativistic jets that flow in opposite directions from the super massive black hole (SMBH). However, the way these emissions depend on the local magnetic environment is poorly understood. Here we simulate how the jet's synchrotron emission depends upon the morphology of the jet's magnetic field structure. We use the PLUTO code to compute 3D hybrid particle-fluid, relativistic magnetohydrodynamic (RMHD) jet simulations. We include Lagrangian particles in our numerical simulations to model synchrotron losses and diffusive shock acceleration while distinguishing the relativistic jet from the cooling ambient medium. Using polarized radiative transfer and ray-tracing (via the RADMC-3D code), we create Full Stokes synthetic radio maps for each magnetic field jet simulation, when the jet carries a predominantly poloidal, helical, and toroidal magnetic field. This allows us to determine the dominant magnetic field structure in radio loud AGN. We find that magnetic field morphologies within the jet have a clear effect on its synchrotron emission: a toroidal field results in an edge-brightened jet whereas a poloidal field highlights the jet's central recollimation shock associated with the radio core. The circularly polarized emission exhibits two signs in the toroidal field case whereas the poloidal jet has only one. Our simulations are consistent with polarized VLBI observations of AGN. We use observational data to create maps of AGN/blazar candidates at 15 Ghz and 22 Ghz showing the characteristic revealed by our simulations.

Brightness temperature distribution and collimation profiles of parsec-scale AGN jets

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The most promising model of Active Galactic Nuclei (AGN) jets suggests that their radio emission is induced by synchrotron radiation from relativistic electrons, which is highly magnified due to relativistic bulk motion close to the line of sight. This yields extreme brightness temperatures at the jet base, which then decrease rapidly downstream the jet. To make a study of the brightness temperature gradients along AGN jets, we analyzed the sample of the brightest AGN jets in the northern sky, that comprises 448 sources observed within the Monitoring Of Jets in Active galactic nuclei with VLBA Experiments (MOJAVE) program at 15 GHz. Using almost 40,000 individual jet component measurements, we analyse variations in their brightness temperature and size to constrain the jet geometry, gradients of a magnetic field strength and particle density. In many sources, the studied distributions can not be described by a single power law, and significant enhancement and broken power law dependence of the brightness temperature is observed at the position of jet knots, bends, and stationary components. There is also an indication that jets, showing transition from a parabolic to a conical shape, are accompanied by the break in their brightness temperature profile. In this talk, we present the results of this study and discuss the observed evolution of the magnetic field and particle density along AGN jets.

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Constraints on the extreme brightness generation mechanisms in AGN from the *RadioAstron* survey and the long-term variability

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Recently, the *RadioAstron* space VLBI mission discovered extreme brightness temperatures, exceeding the inverse-Compton limit for incoherent synchrotron emission of electrons by an order of magnitude or more, in a number of active galactic nuclei (AGN). We jointly analyzed the results of the *RadioAstron* survey of about 250 AGN at 1.7, 4.8, and 22 GHz and their radio light curves at six frequencies from 2.3 to 22 GHz, obtained with the RATAN-600, OVRO, ATCA, and Effelsberg from 2009 to 2020. Statistically significant correlations of brightness temperatures with the simultaneously measured total flux density activity index are found in all three *RadioAstron* frequency bands, as well as with the spectral index measured from several months to two years before the brightness temperature observations. This sheds light on the origins of the extreme brightness temperatures of AGN, showing their connection with major flares in AGN radio cores. Our results demonstrate that, typically, the extreme brightness is generated within the apparent radio core or close to it. This makes such mechanisms for generating extreme brightness as magnetic reconnection, radiation of the electrons with a monoenergetic energy distribution, or coherent processes unlikely. More plausible explanations are Doppler amplification, proton synchrotron radiation, or standing waves in the radio cores.

Multi-Frequency Imaging Results of 452 Extragalactic ICRF-3 Radio Sources from Multi-Epoch, Near-Simultaneous Astrometric VLBA Observations.

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We present multi-frequency images of 452 compact extragalactic radio sources — most of them from the ICRF-3 — with sub-milliarcsecond (sub-mas) resolution, based on Very Long Baseline Array (VLBA) imaging observations taken between April and June 2021. We compare images and astrometry from S (2.3 GHz), X (8.4 GHz), K (24 GHz) and Q-band (43 GHz) in order to study the astrophysical differences and determine the optimal frequency band for Celestial Reference Frame observations. In order to do this we conducted multi-epoch, quasi-simultaneous S/X, K and Q-band astrometric-imaging observations. We characterise each source by the following properties: peak brightness, core and total flux density, the ratio of peak and core to total flux (compactness measure), radial source extent, structure index, source size, and jet direction. We will show how source structure compares amongst all four bands and we will assess the potential advantages of higher radio frequencies for Celestial Reference Frame work.

Decade-long linear polarization variability properties of parsec-scale AGN jets

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We present our results on linear polarization variability of AGN jets at 15 GHz. The images of EVPA and relative fractional polarization variability and median fractional polarization were constructed using multi-epoch VLBA maps with a time span from a few years to almost a quarter of century for 436 sources from the MOJAVE program sample. The core EVPA variability was found to be significantly higher in comparison to that of the jet. The main reason could be the opacity variations in the core region and/or in-beam depolarization. For quasars, the core EVPA is found to be less stable than for BL Lacs confirming our earlier results for a smaller sample. This result seems to be driven by distance difference because for a comparable redshift range the contrast disappears. The analysis of polarization variability along the outflow ridgeline shows that EVPA becomes more stable downstream in the jet in the majority of sources with significant EVPA variability trends along the ridgeline, while the median fractional polarization predominantly increases with core separation. The growth of direction stability and order of magnetic field down the outflow might result in these trends. The relative fractional polarization variability does not show any significant tendencies along and across the jet.

Stellar Evolution Through Maser Studies
(Review)

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Masers - such as silicon monoxide, water, hydroxyl and methanol - probe a number of stages of stellar evolution including star-formation, asymptotic giant branch stars, proto-planetary nebulae, red supergiants and supernova remnants. Compact and of high brightness temperature, the masers can be used to perform studies at high-angular resolution using radio and mm/submm interferometry. The studies can determine gas physical conditions, in conjunction with radiative transfer modelling; gas kinematics (3D velocities can be obtained using proper motions); information on magnetic field strength and morphology; and, distance measurements. In this talk, I will outline recent results for masers in the area of stellar evolution highlighting the contributions of VLBI and EVN observations, and the synergies of these with data from other telescopes such as ALMA.

Yet another 6.7 GHz imaging of the high-mass star-forming region Cep A HW2

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Due to high brightness and low interstellar extinction at 6.7 GHz, class II methanol masers are useful for studying the physical properties of massive young stellar objects. Since they usually originate within 1000 AU from the protostar and are pumped by IR photons, their variability can be a decent marker of protostellar activity. Our monitoring of the 6.7 GHz methanol masers in Cep A revealed quasi-periodic low-amplitude red-shifted flares. Thus we decided to examine this phenomenon closer in EVN projects RD002 and ED046B.

Cepheus A is a well-known, well-studied high-mass star-forming region located only 700 pc away, which hosts a cluster of young stellar objects. The brightest continuum source, HW2, is an HMYSO with a mass of $\sim 10\ M_{\odot}$ and bolometric luminosity of $2 \times 10^{4}\ L_{\odot}$.

Our results, combined with previous VLBI observations, pinpoint flaring cloudlets near the presumed edge of a dust emission core and show nearby blue-shifted emission that is not visible on single-dish spectra due to blending and also appears to show periodic variability.

6.7 GHz CH_3OH masers polarization in massive star-forming regions: the Flux-Limited Sample.

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The formation process of high-mass stars ($M > 8M_{sun}$) is still unclear; this is mainly due to their fast evolution and large distances that make difficult to observe them in details. The observational and theoretical efforts made in the last decades have shown that a common and essential component in the formation of high-mass stars is the presence of molecular outflows during the protostellar phase, similarly to what is observed during the formation of low-mass stars. Theoretically, it has been convincingly demonstrated that the magnetic field plays an important role in launching and shaping molecular outflows in massive young stellar objects (YSOs). Although there is a large consensus on the theoretical importance of magnetic fields in launching the outflows, there are still some open issues from an observational point of view. For instance, the alignment of the magnetic field lines with the outflows. Therefore, providing new measurements of magnetic fields close (10s-100s au) to massive YSOs is of great importance. This can be achieved only by observing the polarized emission of molecular masers by using the VLBI technique. More than 10 years ago we started a large EVN campaign to measure the magnetic field orientation and strength towards a sample of 30 massive star-forming regions, called the "flux-limited sample", by observing the polarized emission of 6.7 GHz methanol masers.In this talk I will present the final statistics of the flux-limited sample, as reported in Surcis et al. (2022, A&A, 658, A78), which are focused on the relative orientation of the outflows with the magnetic fields and with the maser distributions, and on the polarized characteristics of 6.7 GHz methanol masers. These are the linear and circular polarization fractions (P_l and P_V) and the Zeeman-splitting that we were able to measure towards a large number of methanol maser features.

3D Models of Astrophysical Masers with Polarization

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Spatial polarization variations, including rotations of the electric vector position angle within single VLBI features, have been detected in the circumstellar envelopes of the Mira variables TX Cam and R Cas. We describe early results of a 3D maser radiative transfer code that includes polarization, and has been written to aid the analysis of spatial gradients in polarization within single clouds. The code considers saturation of inversions at the electric field level, so that a solution of the problem requires solving a set of non-linear algebraic equations directly in the off-diagonal elements of the density matrix. Diagonal elements (inversions) are then derived from the solution. We describe tests of the code that use tubular domains of various aspect ratios for comparison with earlier 1D models, before considering more general cloud shapes.

The e-MERGE e-MERLIN/VLA/EVN wide-field deep radio survey of GOODS-N

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The initial description paper for the e-MERGE deep (∼1μJy/bm), (30x30 arcmin^2 field) high-resolution (∼1.5 - 0.25 arcsec) radio survey of GOODS-N is now published[**1**]. Images are now available to the e-MERGE consortium from Data Release-1 (DR-1) covering the inner central 15x15 armin^2 region. This release involves a VLA 5.5GHz mosaic (∼0.5arcsec beam, 1.5μJy/bm) + a VLA-only 1.5GHz (42-hrs) image + combination VLA + e-MERLIN images (25% of the deep 1.5GHz data - 108hrs, 4.5/18 days). The latest results from joint e-MERLIN+VLA 1.5GHz imaging are presented along with a short discussion of combination imaging of datasets with differing sensitivities. The e-MERGE results demonstrate the ability of high-resolution imaging at 1.5GHz to spatially resolve regions of radio emission associated with star-formation within the 848 DR-1 catalogued radio sources out to z=3 and differentiate such regions from those associated with actively accreting AGN-jet systems.

The DR2 enhancement is under way utilizing all the e-MERLIN+VLA 1.5GHz (unaveraged) data and imaging out to the full 30x30 arcmin^2 field of view, which will produce a single wide-field image to a depth of ∼500nJy/bm in the inner 7.5 arcmin diameter field and ∼1μJy/bm in the surrounding outer annulus - a factor of x4 increase in field size and x2 increase in depth in the inner region.

An additional 24-hrs of (associated) e-MERGE 1.5GHz data were observed with the EVN [**2**] providing mas-scale resolution at 582 correlation positions centered on the e-MERLIN field, the vast majority of which lie within the DR-1 area (central sensitivity ∼9μJy/bm, beam ∼5mas.) Initial results for combination EVN+e-MERGE 1.5GHz imaging from a sample of 31 AGN-dominated radio sources are discussed with regard to the majority being compact core+(galactic-scale) extended radio structures, possibly the high-redshift tail to the local Universe FR0-type radio structures [**3**], the most common form of radio AGN systems found in the Universe.

[**1**] T.W.B. Muxlow, et al., MNRAS **495**, 8, May 2020, pp 1188-1208.

[**2**] J.F. Radcliffe, et al., A & A **619** A48, 31, July 2018, pp. 1-14.

[**3**] R. D. Baldi, A. Capetti, & F. Massaro, A & A **609** A1, 22 August 2017, pp. 1-10.

SPARCS-North Survey: Exploring the resolved μJy extra-galactic radio source population with EVN+e-MERLIN

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The SKA PAthfinder Radio Continuum Surveys (SPARCS) are providing deep-field imaging with multiple SKA precursors such as the MeerKAT, LOFAR, ASKAP, *e*VLA and eMERLIN. To characterize the relative contribution of radio emission associated with AGN from star-formation (SF) in faint radio source populations, a combination of sensitivity and high angular resolution imaging over a range of spatial scales (arcsec to mas) is required. We present a multi-resolution (10–100 mas) view of the transition between compact AGN and diffuse SF through the deep wide-field EVN+e-MERLIN, multiple phase centre survey of the centre of the Northern SPARCS (SLOAN) reference field at 1.6 GHz. This survey provides the first (and only) VLBI (+e-MERLIN) resolution observation of this field, and of the wider SPARCS reference field programme. We present a catalogue of 11 VLBI sources detected in the SPARCS-North field based on a sample of 52 known radio sources from previous observations with the eMERLIN. We provide high spatial dynamic range coverage of these sources at $\sim$ 9 pc –0.28, further complemented by VLASS and e-MERLIN imaging at kpc and sub-kpc spatial scales, respectively. VLBI observations reveal compact emissions at parsec scales with one-/two-side jet structure appearing at sub-kpc scales. While the eMERLIN resolves diffuse revealing extended radio structure associated with typical radio galaxies, the VLASS is important for source identification. Combining these spatial scales, we have made a serendipitous discovery of a binary SMBH candidate within the SPARCS-North field. It is expected that the occurrence of such sources are common but are however limited by sensitivity of our radio instruments and the FoV. Advances in the wide-filed VLBI technique and its application opens up possibilities for new discoveries of important astrophysical objects at mas scales over wide areas. An increase in the sensitivity of radio surveys and the increasing ability to probe the dynamic radio sky at VLBI mas scales, will directly probe the missing population of dual-AGN and binary SBMHs, which is crucial for SKA surveys. This VLBI+eMERLIN survey provides angular resolutions that will not be matched until SKA Phase 2. Therefore, this survey provides a source classification training set for the near-future deep-wide field VLBI surveys with instruments such as the MeerKAT and the SKA.

The LeMMINGs survey: probing sub-kpc radio structures of nearby galaxies with e-MERLIN

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Nearby galaxies represent ideal laboratories for studying galaxy evolution, star formation (SF) and super massive black holes because they are close enough to resolve individual sources. For this reason, e-MERLIN and it's combination of sub-arcsecond-resolution with sub-mJy sensitivity, is an ideal telescope for studying sub-kpc-scale jet activity from low-luminosity active galactic nuclei (AGN) in nearby galaxies. Such a study has been undertaken as part of the Legacy e-MERLIN LeMMINGs survey. LeMMINGs is designed to be statistically-complete to all galaxy morphological and AGN types, performing a census of AGN activity and SF for 280 galaxies in the nearby (d¡100 Mpc) Universe. These 280 sources have been observed with e-MERLIN at 1.5 and 5 GHz, and have copious amounts of ancillary multi-wavelength data also, allowing for multi-wavelength correlations to be investigated.

In this talk, I will give an overview of the current status of the LeMMINGs survey, focussing on the key science highlights from the 1.5 GHz survey (Baldi et al. 2018,2020,2021) as well as the *Chandra* X-ray (Williams et al 2022) and the *Hubble* optical (Dullo et al. submitted) ancillary work. I will also discuss preliminary results from the 5 GHz survey (Williams et al. in prep) and how they are shaping our understanding of the 1.5 GHz work already undertaken. In total, 106/280 of the galaxies were detected with radio sources coincident with the optical galaxy nucleus in the 1.5 GHz sample. Most of these are unresolved 'cores', but a third of sources show jetted morphologies, likely due to AGN activity. I will highlight the "jetted HII region" galaxies which show jet-like nuclear morphologies, indicating some AGN activity, but missed in previous surveys due to their lack of optical line emission. I will also highlight some of the radio/X-ray and radio/optical correlations, showing how different AGN types like Seyferts and LINERs appear to fall in different regions of these plots and therefore are due to different accretion mechanisms. Finally, I will briefly discuss the future aspects of the LeMMINGs survey, including the future multi-wavelength aspects including *Hubble* images, widefield radio imaging and deeper studies that have begun due to the LeMMINGs programme.

The Mass Distribution in the Central Region of the Milky Way and Dynamics of the Galactic Bar

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Understanding the mass distribution and associated dynamics of the inner 4-kpc of the Milky Way is very challenging because of high obscuration at optical wavelengths and our ability to accurately measure the distance and 3D motions of sources at these distances. Using trigonometric parallax observations of inner-Galaxy sources we have been able to refined the universal galactic rotational curve published in Reid et al. (2019), for galactocentric distances below 4 kpc. We present evidence that the young, high-mass star formation regions in the inner galaxy are located in gas following elliptical orbits. These represent the first direct measurements of the dynamics of the Milky Way's bar and we compare the derived parameters with those inferred from stellar density and other indirect means.

The radio nucleus of the nearby dwarf galaxy NGC 4395

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The dwarf galaxy NGC 4395 is located at z = 0.00106 (about 4.3 Mpc) that allow us to do observational studies at an extraordinarily high spatial resolution of 0.02 $\mathrm{pc\,mas^{-1}}$. As an extremely low-luminosity, it hosts an intermediate-mass black hole (IMBH) with a mass between $\sim 10^4$ and $\sim 10^5$ solar masses. The High Sensitivity Array (HSA) observations at 1.4 GHz in 2005 found a sub-mJy outflow-like feature in its radio nucleus. To probe its possible physical connection with the accreting IMBH, we conducted the deep VLBI observations with the EVN at 5 GHz and investigated the additional archival data observed by the HSA at 1.4 GHz in 2008, the Jansky Very Large Array (VLA) at 12–18 GHz and the Atacama Large Millimeter/submillimeter Array (ALMA) at $\sim$237 GHz. The outflow-like feature displays a more diffuse structure in the HSA image of 2008 and has no compact feature detected in the 5-GHz EVN image. Together with the optically thin steep spectrum and the large angular offset (about 220 mas) from the accurate optical *Gaia* position, we interpret the non-thermal feature as nuclear shocks likely formed by IMBH ejection activity. In the VLA and ALMA images, we find a sub-mJy diffuse feature surrounding the accreting IMBH. Moreover, there is no jet base detected at $\geq$0.035 mJy beam^{-1} (5σ) in the two VLBI maps.

Maser Astrometry (Review)

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We introduce background and context for the contributed talks given in the Astrometry session. We also review recent scientific achievements with Maser Astrometry, such as the Galactic structure, and an accretion event in the high-mass protostar G358.93−0.03-MM1. The VLBA BeSSeL and VERA projects have compiled more than 200 VLBI astrometric results, which reveals that the Milky Way is a barred spiral with four major arms and extra arm segments and spurs. The results update the Galactic constants to be $(R_0, \Theta_0) = (8.15 \pm 0.15$ kpc, 236 ± 7 km s$^{-1})$. The circular velocity at the solar position Θ_0 is larger than the IAU 1985 recommended value (220 km s^{-1}). It indicates that the Milky Way is heavier than previously thought since the total mass of the Milky Way is $\propto \Theta_0^3$ in the NFW dark halo potential. The "episodic-accreation" theory of high-mass star formation was observationally confirmed for G358.93−0.03-MM1 by the Maser Monitoring Organisation (M2O) gathered several radio telescopes in the world. The proper motion of G358.93−0.03-MM1 was measured to be 1−2 mas (milliarcsecond) Day^{-1} (11,700−23,400 km s^{-1} at $d = 6.75$ kpc) by observations of 6.7 GHz methanol masers. Such a fast motion could be explained under the hypothesis of an accretion event in which enhanced far-infrared radiation drives the production of the methanol masers.

Ultra-wide band polarimetry using VERA

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This talk presents a review on front- and back-end developments for 20m radio telescopes of VLBI Exploration of Radio Astrometry (VERA). We show a brief overview of currently ongoing technical developments of a dual circular polarization receiving and ultra-wide band (16 Gbps) recording systems that have been installed to each of four telescopes of VERA. With these developments of the wide band VLBI polarimetry, we study magnetic field properties of radio jets in active galactic nuclei at unprecedented sensitivity. The observing performances obtained from most recent VLBI experiments are also presented.

"How to" MultiView - A guide for 10μas astrometry

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The benchmark accuracy for trigonometric parallaxes in the current era is 10 μas, representative of 20 μas-per-epoch positional accuracy. This can also be considered the current limit, and is mainly achieved at higher frequencies (e.g. > 20 GHz) where the presence of the ionosphere is smaller. Since we developed inverse Multiview (an amalgamation of inverse phase referencing and Multiview) we have consistently achieved parallax accuracies ~ 10 μas (e.g. Figure 1) on our four-antenna array of 2x12m and 2x30m dishes operating around 7 GHz. Our current limitation appears to be thermal in nature, implying that future observations with larger arrays of sensitive telescopes may very well achieve accuracies $\ll 10$ μas. We will show off our most recent results, and more importantly, discuss the scheduling, observation and calibration considerations necessary to achieve similar or (very likely) better accuracy on the EVN. This will include a discussion of inverse vs. direct vs. 'true' Multiview, use cases as a function of frequency, and tools we are developing to assist with this overall process.

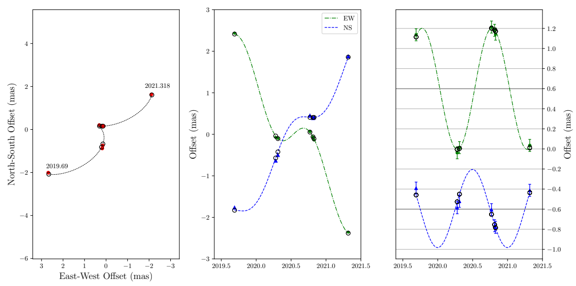

Figure 1: Example parallax and proper motion modelling of class II 6.7 GHz methanol maser G232.62+0.99. Measured parallax and proper motions are $\varpi = 0.611 \pm 0.011$ mas, $\mu_x = -2.266 \pm 0.021$ mas/yr and $\mu_y = 2.249 \pm 0.049$ mas/yr.

VLBI MultiView Astrometry of Radio Stars

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Some M-dwarfs are radio loud beyond what could be expected from the Güdel-Benz relationship (which correlates stellar activity in X-ray and radio). Expected emission mechanisms include steady state plasma emission, gyrosycnhrotron during short-lived (<2 hrs) flares, and Electron Cyclotron Maser Instability (ECMI) which can occur in planetary aurorae, and interactions between a star and a planetary or stellar companion. With a sufficiently strong magnetic field, ECMI emission can reach GHz frequencies.

VLBI enables us to study the nature and location of the emission of nearby M-dwarfs. We are implementing our own version of the MultiView technique to correct for ionospheric disturbances, which should lead to an astrometric accuracy for the VLBI data comparable to Gaia data. This allows us to compare the location of the optical and radio emission. The emission could originate from outside the star itself, but an offset could also be due to reflex motion, modeling errors or calibration residuals.

In this contribution, I'll discuss the observations we have carried out on a number of radio loud M-dwarfs, in particular on Ross 867 and WX UMa. We have several epochs of data on the first source, which should allow us to measure proper motion and parallax independently of the GAIA data. For WX UMa, our first observation has shown a significant positional offset of over 50 stellar radii between the radio emission and the expected stellar position.

TeV detected AGN jets in the TANAMI program

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The radio band holds the key to solve some of the most pressing problems in high-energy astrophysics: The short timescales of very high energy gamma-ray variability and broadband spectral energy distribution (SED) models of high-peaked BL Lac objects suggest Doppler factors that are much higher than the values obtained from radio measurements. This problem is known as the Doppler crisis. In the case of TeV-detected quasars, their short-timescale variability suggests that the γ–ray emission originates from very compact regions but the compact base of the jet seems excluded because it is not clear how the high–energy photons may escape from within the broad line region. There are some suggestions to resolve these contradictions, e.g. a spine–sheath structure in the jet that may be detectable with VLBI, but a clear answer has evaded us so far. Larger samples of sources and high-quality VLBI data can help us to make progress in solving these puzzles. Since most previous studies only involved northern sources, we aim to improve statistics and sky coverage by adding sources that can only be observed with southern-hemisphere telescopes. TANAMI is currently the sole VLBI monitoring program targeting southern sources, providing the only tool to probe their intrinsic jet properties and to track the morphological changes in the innermost region of these AGN. With quasi-simultaneous data from the *Fermi*/LAT, the link between the radio and GeV gamma-ray variability is continuously being investigated. Here, we will focus on $\sim$20 TANAMI sample sources that have also been detected at very high energies. We discuss parsec-scale jet properties and kinematics of sources that have been monitored over several years and report on first observations of the complete southern-hemisphere TeV AGN sample.

Correlations of the multiwavelength emission in the blazar CTA 102 during 2016-2018

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Blazars are among the most powerful objects in the universe. Their relativistic jets pointing towards Earth show variable flux density across the entire electromagnetic spectrum. The Fermi Large Area Telescope observed the active γ-ray states in the blazar CTA 102 from 2016 to 2018. During this period, we find two prominent γ-ray flares. In this study, we investigate correlations of the multiwavelength emission to figure out the nature of the γ-ray flares. The multiwavelength light curves from radio to X-ray energies show the flares that seem to be associated with the γ-ray flares. We employ the discrete correlation function and find a $> 2\sigma$ correlation between the radio and γ-ray energies. The optical/X-ray emissions show $> 3\sigma$ correlations with the γ-ray emission. Moreover, we use the 43 GHz Very Long Baseline Array (VLBA) data to explore the kinematics and flux variability in the parsec-scale jet of this source during the γ-ray flares. We find that a moving jet component passes through a stationary one during the first γ-ray flare. The second γ-ray flare is associated with an ejection of a new jet component from the radio core. Based on the results of the correlation analysis and the jet kinematics, we discuss the possible origins of the γ-ray flares.

Growing evidence of the blazar - neutrino connection

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We have found significant observational evidence that high energy neutrinos are generated in VLBI-selected blazars and arrive preferentially during their flares. In this talk, we present new results from a joint analysis of VLBI, single-dish radio and neutrino data from IceCube, ANTARES, and Baikal which support and further strengthen this conclusion. In particular, we discuss new high energy neutrinos which were recently detected from the direction of blazars which we signaled previously as highly probable neutrino associations. We conclude the presentation by outlining exciting new opportunities for VLBI studies in the era of multi-messenger astronomy.

A VLBI investigation of high-energy neutrino emitter candidates

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Theoretical models predict that the inner part of blazars jets are the site in which particle acceleration takes place and high-energy neutrinos are produced. The interest of the multi-messenger community to blazars as possible neutrino counterparts was powered up in 2017, when a high energy neutrino was detected in close proximity with the blazar TXS 0506+056, which was also flaring in gamma-rays. The high angular resolution observations with VLBI provide crucial tests for the association of neutrinos with blazars. Indeed, the VLBI follow-up observations led to unveil VLBI-scales properties in the TXS 0506+056 jet potentially connected with the neutrino production. However, since then, the general picture on the high-energy neutrinos origin and their possible association with gamma-ray blazars has remained unclear. In particular, radio jets have been proposed as a promising site for the production of the astrophysical neutrinos, calling for a systematic study of these systems.

In this context, we aimed to add new pieces to this puzzling scenario with the VLBI investigation of gamma-ray blazars observed in spatial coincidence with four new neutrino events, detected by the IceCube observatory between 2019 and 2020. We compared our new observations obtained just after the neutrino detections with past VLBI data for selected candidate counterparts. This allowed us to search for hints of possible connection between the neutrino events and those sources. In particular, for some of the proposed candidates, we exploited the high sensitivity capabilities of the EVN (Nanci et al. 2022). In this talk, I will show you the results of our first explorative VLBI follow-up campaign, focusing on a few peculiar and most promising targets.

Direct confirmation of the VLBI-Gaia offsets nature

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A major result of the Gaia mission is the detection of significant offsets between optical and VLBI positions of AGNs. In previous work, we argue that these offsets are primarily due to the presence of optical jets. We followed this discovery up with dedicated observational campaigns. Here, we report on the updates brought by the most recent Gaia Data Release, and present early results from observations by the Hubble Space Telescope and the EVN. We have already confirmed several optical jets and found hosts with prominent dust lanes. These sources were predicted on the basis of VLBI and Gaia astrometry, and constitute the most direct confirmation of the nature of radio-optical offsets.

EHT Observations of Supermassive Black Holes and Relativistic Jets
(Review)

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The Event Horizon Telescope (EHT) Collaboration has recently released the first 1.3 mm image of the Galactic Center black hole, Sagittarius A* (Sgr A*). The image reveals a bright, thick ring with a diameter of 52 µas and a comparatively dim interior. The size of the ring is consistent with the expected appearance of a Kerr black hole with a mass of $\sim 4 \times 10^6\, M_\odot$ at a distance of ~8 kpc. Together with the M87* image published in 2019, the results suggest that lensed rings are universal features of black holes and that general relativity can consistently predict this across three orders of magnitude in black hole mass.

Besides the two horizon-scale targets, the EHT also observes several bright AGNs (e.g., 3C 279, Cen A, J1924-2914), providing unprecedented angular resolutions of their relativistic jets.

The EHT observations at 1.3 mm are often accompanied by coordinated multi-wavelength (MWL) campaigns, including VLBI observations at longer wavelengths. The MWL observations help maximize the scientific outputs of the EHT campaign.

In this talk, we will review the details of the observations, the data analyses, and the role of MWL observations in the EHT 2017 campaign, especially the need for quasi-simultaneous longer-wavelength VLBI observations.

M87 jet instability probed by multi-frequency observations

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We present the results of a multi-frequency study of Kelvin-Helmholtz instability developing in the jet in M87, based on of full-track VLBA observations at 8 and 15 GHz, and Radioastron observations at 1.7 and 5 GHz. All Stokes I images show multiple oscillatory patterns with up to three regular threads developing and propagating inside the jet on scales up to 400 mas. Thus, radio images show a spiral-like jet structure. The pattern observed in the spectral index map between 8 and 15 GHz is also consistent with observed threads. In addition, the global jet bending is observed at a core separation of $\sim$100 mas that also can be induced by the instability. We quantify the observed structural patterns by measuring transverse intensity profiles along the jet and modelling them with multiple Gaussian components. This analysis shows evidence for growing oscillatory patterns which are consistent with the helical and elliptical surface and body modes of Kelvin-Helmholtz instability developing on scales from 5 to 400 milliarcseconds.

Spectral Analysis of Parsec-Scale Jet in M87: Observational Constraint on the Magnetic Field Strengths in the Jet

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Because of its proximity and the large black hole size, M87 is one of the best targets for studying the launching mechanism of the AGN jets. Currently, magnetic (B) fields are considered to be an essential factor in the launching and accelerating of the jet. However, current observational estimates of the B field strength of the M87 jet are limited to the innermost part of the jet ($\lesssim 100\ r_s$), or HST-1 ($\sim 10^5\ r_s$). No attempt has yet been made to measure the B field strength in between. We aim to infer the B field strength of the M87 jet out to a distance of several thousand r_s by tracking the distance-dependent changes in the synchrotron spectrum of the jet from high-resolution VLBI observations. In order to obtain high-quality spectral index maps, quasi-simultaneous observations at 22 and 43 GHz were conducted using KVN and VERA (KaVA) and the VLBA. We compare the spectral index distributions obtained from the observations with a model and place limits on the B field strengths as a function of distance. The overall spectral morphology is broadly consistent over the course of these observations. The observed synchrotron spectrum rapidly steepens from $\alpha_{\text{22-43 GHz}} \sim -0.7$ at ~ 2 mas to $\alpha_{\text{22-43 GHz}} \sim -2.5$ at ~ 6 mas. In the KaVA observations the spectral index remains unchanged until ~ 10 mas but this trend is not clear in the VLBA observations. A spectral index model in which non-thermal electron injections inside the jet is decreasing with distance can adequately reproduce the observed trend, and it suggests the B field strength of the jet at a distance of $2 - 10$ mas ($\sim 900\ r_s - \sim 4500\ r_s$ in de-projected distance) has a range of $B = (0.3 - 1.0\ \text{G})\,(\text{z}/2\ \text{mas})^{-0.73}$. Extrapolating to EHT scale yields consistent results, suggesting that the majority of the B flux of the jet near the black hole is preserved out to $\sim 4500\ r_s$ without significant dissipation.

Unveiling spectral view of the M87 radio jet

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The spectral index images of the jet in the nearby radio galaxy M87 have previously been shown with Very Long Baseline Interferometric arrays at 2-43 GHz. They exhibit flattening of the spectral index at a location of inner (central) spine and toward outer ridges. This could imply optical depth effects, lower energy cutoff or stratification of the emitting particles energy distribution. We employ simulations with various model brightness distributions and show that the observed spectral index images are affected by systematic effects that both flatten the spectra in a series of ridges and steepen in low surface brightness regions. These types of the imaging artefacts do not depend on the model considered. Meanwhile, the central spine of M87 radio jet is consistent with optically thin constant spectral index value. We propose a methods for the compensation of the systematics using only the observed data.

Fast Radio Bursts
(Review)

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Fast Radio Bursts (FRBs), exotic micro-millisecond duration radio signals, are currently the hottest topic in transient radio astronomy. Their discovery have sparked a flurry of theoretical studies into their origin and physics, as well as global observational efforts to look for more such bursts. We've learned a lot about FRBs in the last decade or so and thanks to interferometric observations, we can now routinely localise the bursts to their host galaxies with (milli-) arcsecond accuracies. In the absence of multi-wavelength counterparts to extragalactic FRBs, analyses of their host galaxy and local environments are presently the most informative path to identifying FRB progenitor systems. Furthermore, localised bursts also allow us to use them as probes to trace ionised gas in galaxy haloes, large-scale structure, and the inter-galactic medium. In this talk, I'll provide a brief overview of our current understanding, with a particular emphasis on the role of VLBI observations of FRBs.

Milliarcsecond localizations as insights of the local environments and origins of Fast Radio Bursts

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Fast Radio Bursts (FRBs) are extremely luminous and brief signals (with duration of milliseconds or even shorter) of extragalactic origin. Despite the fact that hundreds of FRBs have been discovered to date, their nature still remains unclear. The inferred cosmological distances of FRBs have important implications for a wide variety of research fields, and thus the physical origin of FRB emission is currently one of the most compelling problems in astrophysics.

The European VLBI Network (EVN) is currently the only instrument capable of localizing FRBs down to the milliarcsecond level. This level of precision is critical to unveil not only their host galaxies but their local environments. The study of these environments is the most plausible way to shed light on the physical processes that lead to the burst production.

Our team has localized a handful of FRBs using the EVN, revealing surprising and unexpected environments. Some of them have been found next to star-forming regions, suggesting the scenario of being associated with very young objects (from tens to thousand years old magnetars). However, our last finding of a FRB inside a globular cluster associated to the M81 galaxy broke this case, at least for part of the population.

In this talk we will make a review of the field of FRBs, our latest discoveries, and how these are interpreted towards the path of unveiling the processes that create these bursts.

The nature of radio emission from the tidal disruption event AT2019dsg

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A tidal disruption event (TDE) involves the cataclysmic shredding of a star in the vicinity (at or within the tidal radius) of a galactic supermassive blackhole (SMBH; $10^6 - 10^8\ M_\odot$). The nearby ($\approx$ 230 Mpc) relatively radio-quiet, thermal emission dominated source AT2019dsg is the first TDE with a potential neutrino association. Non-thermal emission from TDEs can involve physical processes in an outflow (relativistic/collimated or non-relativistic/wide-angled). Monitoring very long baseline interferometry (VLBI) observations of AT2019dsg can help address the origin of radio emission, and clarify mechanisms for the production of neutrinos. High-resolution European VLBI Network (EVN) 5-GHz observations were conducted over three sessions spanning 4 months during 2019 – 2020, with AT2019dsg detected in all sessions. The EVN astrometric measurements and flux density evolution provide less evidence for a relativistic emitting component (at the 3-σ uncertainty level). This and modelling the 5 GHz flux density evolution point to emission from a decelerating shock produced by a fast outflow ($\approx$ 0.1 c) that had interacted with a dense surrounding medium. The base of the outflow is found to offer suitable conditions for the production and acceleration of cosmic ray protons and neutrinos. The findings promote an expanded inventory of multi-messenger (electromagnetic, particles: cosmic rays and neutrinos, gravitational waves) producing transients, not necessarily requiring a powerful accelerating mechanism such as a relativistic jet. We present and discuss results from the study of AT2019dsg including the key role played by the EVN astrometric and flux density measurements in enabling the above inferences.

Multi-wavelength studies of low-mass X-ray binaries: accretion and feedback around stellar-mass compact objects
(Review)

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The inflow of matter onto astronomical objects is connected to the generation of outflows throughout the Universe on a variety of scales, from proto-planetary disks, to merging neutron star systems and gamma ray bursts, to stellar mass and supermassive black holes.

The matter inflow/outflow processes scale predictably with mass, and proceeds according to the same basic principles around all collapsed objects. Super-massive black holes have driven the evolution of galaxies and regulated star formation through accretion and feedback. In accreting binaries - the low-mass counterparts of super-massive black holes - a stellar mass black hole or a neutron star feeds from an accretion disc that is formed by the material stripped from a stellar companion.

I will give an overview of the phenomenology ascribed to the accretion process and to the generation of outflows in low-mass X-ray binaries, and I will show how these processes can be understood only if studied together. I will also demonstrate that the study of fast-time variability of accreting binaries constitutes an invaluable tool that allows to probe the physics underlying the disc-jet coupling in ways inaccessible to other analysis techniques. While the focus of this talk will be on black hole systems, I will also show how neutron stars are ideal laboratories to study the accretion-ejection processes.

Finding quiescent black holes with VLBI

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Black hole X-ray binaries (BHXBs), accreting systems of a stellar-mass black hole and a star, are perfect proxies to probe fundamental physics. To date, most known BHXBs have been first detected from X-ray or optical emission during an outburst, leaving the quiet BHXB population undiscovered. Most BHXB population studies are thus affected by a selection bias. In this talk, I will discuss a technique to find the much larger, hidden BHXB population in our Galaxy. We measured the proper motions of 33 highly variable, compact, flat spectrum sources that are concentrated towards the direction of the Galactic plane. Confirming that these sources are a part of our Galaxy and not extragalactic AGN is the first step in identifying the BHXB population from this sample. We found at least two strong candidates that are moving with high proper motions, implying them to be Galactic and hinting towards their quiescent BHXB nature. We also found that the rest of the population is a spicy mix of varied sources. I will discuss these results and show how this technique can be used to search for exotic Galactic transients.

Anatomy of an exo-aurora: the magnetosphere of a brown dwarf

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At the very low mass regime of stellar and substellar objects, ultra-cool dwarfs (UCDs) cover the boundary between stars and exoplanets where radio observations have already proved the existence of powerful magnetic fields. Such observations are crucial not only to directly measure the strength and topology of the UCDs' magnetic fields but also for opening a new route for the detection of exoplanetary radio emission, and hence, establishing a novel tool to discover new worlds. The way that the mechanisms behind UCDs radio emission operate is not fully understood although there are some promising models: (gyro)synchrotron and auroral emission.

Dozens of UCDs have been detected at GHz frequencies but only three of them have been successfully detected with very long baseline interferometry (VLBI) arrays. This technique may provide a critical piece of the puzzle as it can resolve the magnetosphere of nearby UCDs providing a new window to better understand these objects. Up to this date, there is no report on such achievement as all three VLBI detections showed unresolved sources.

In this talk we will present the results of an EVN campaign of four nearby UCDs and will focus on one object where the magnetosphere has been clearly resolved. Remarkably, we are able to detect changes in the morphology of the magnetosphere across our observation. Additionally, the object shows a circularly polarized burst of radio emission that seems to be linked to auroral emission. We will discuss the implications of these results and the possible scenarios that attempt to reproduce it.

Filming the evolution of symbiotic novae with VLBI: the 2021 explosion of RS Oph

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Fifteen years after its previous outburst, the symbiotic recurrent nova RS Oph exploded again on 2021 Aug 8th, its first outburst during the *Fermi* era. In symbiotic novae, the material ejected from the surface of the white dwarf (WD) after the thermonuclear runaway drives a strong shock through the dense circumstellar gas produced by the red giant (RG) wind. This nova is a perfect real-time laboratory for studying physical processes as diverse as accretion, thermonuclear explosions, shock dynamics and particle acceleration; in many ways it is like a supernova remnant on fast forward. The experience of its previous outburst and of 2010 V407 Cyg (the only symbiotic nova that has ever occurred during the *Fermi* era), indicates that a large sensitivity and a broad range of baseline lengths are necessary to follow its evolution over a period of several weeks. This would provide unique constraints on major outstanding problems, including the emission mechanisms, the physical processes at work, the presence and location of shock acceleration, the geometry of the system, and the density of the RG wind. We will present preliminary results from the EVN+e-MERLIN observations carried out on weeks/months time scales after the August explosion and a comparison with the constraints derived from optical spectroscopy.

Minor Flares on Cygnus X-3 – VLBI Prospects

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The cm-wavelength radio flares on Cygnus X-3 have been studied for many years. Our recent paper (arXiv:2203.05637) looked again at the minor flares (flux density S of a few 100 mJy), and compared their properties with those of a sample of major flares (S > 1 Jy). We find that the minor flares have have rise times and duration of $\sim$ 1 hour, as opposed to $\sim$ days for the major flares. Minor flares show more rapid expansion of the synchrotron radiation emitting material than in the strong flares. They also appear closer to the binary, whereas the large flares form a more developed jet, i.e minor flares are short and fat, major flares long and thin.

We used the results of Fender and Bright (2019) to calculate the magnetic field and expansion velocity β under minimum energy conditions when the source is optically thick for samples of minor and major flares. The minimum power in the source was found using the rise time of the flares. The minor flares have lower minimum power but have larger velocities and energy densities than the major flares. Minor flares can occur while a major flare is in progress, suggesting an indirect coupling between them. The spectral evolution of the minor flares can be explained by either an expanding synchrotron source or a shock model. Some of the minor flares are double possibly due to a brightening zone as in SS433.

Further investigation requires high resolution VLBI observations at the 1 mas level if we wish to understand the development of the source and indeed confirm a brightening zone. The problem is that Cygnus X-3 is strongly scattered by the interstellar medium so high frequencies in the several 10s of GHz are required for the resolution needed. The minor flares are rapid and require high cadence observations to follow the flux density behaviour and hence only short snapshot VLBI observations can capture the structure. Large number of telescopes are required which is a problem at the highest frequencies. We discuss the VLBI possibilities and trade-offs for this awkward object.

The first look at the coincidence of methanol and excited OH masers around HMYSOs

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Observational studies of high-mass young stellar objects (HMYSOs) at radio wavelengths are necessary to answer the question about high-mass star formation. Significant contributions to our knowledge of the formation of HMYSOs came from interferometric observations of cosmic masers, mainly OH, methanol and water transitions. We imaged a sample of 14 sources where the excited OH maser line at 6.035 GHz exists and the 6.7 GHz methanol maser line using eMERLIN. We present preliminary results for the first three targets, well known high-mass star-forming regions. We have found the coincidence of maser clouds at both transitions and also their avoidance. That allows us to verify the theoretical models of maser emission and get to know better the physical conditions in structures surrounding HMYSOs.

Cloudlet evolution in IRAS 20126+4104 during last 15 years and it's periodic variability

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We are reporting results of EVN observations and single dish monitoring towards IRAS 20126+4104. EVN archive data reviles that overall morphology hasn't changed significantly during 15 years, and 7 cloudlets can be found in all 5 epochs. However individual cloudlets morphology changes noticeably, there shape varies from linear to helix like. Position angle also varies highly epoch to epoch indicating turbulent environment. In most instances velocity gradient is well expressed, but average value is relatively low 0.18 km s^{-1} mas^{-1}. Single dish monitoring show two distinctive trends, first long term dimming and recovery of blue shifted spectral components, and second quasi – periodic variability with around 36 day period starting from April 2020. All spectral features varies synchronously and with stable phase delays, consistent with light speed propagation. There sequence is in an agreement with this source YSO model proposed by Moscadelli et al. (2011) and Surcis et al. (2014). There is still no report of detection of the ultra compact HII zone towards IRAS 20126+4104, that in combination with variability pattern and morphology in our opinion suggest that we ar witnessing surge in accretion rate causing instability in central early B type star like proposed by Inayoshi et al.(2013).

IC 485: A new disk-maser galaxy?

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Extragalactic maser sources associated with the Active Galactic Nuclei (AGN), named megamasers, are unique tools to derive fundamental physical quantities of the host galaxies. Those associated with accretion disks around the supermassive black holes (SMBH) are used to trace the disk geometry, to estimate the BH mass and to measure accurate distances to their host galaxies. Masers associated with radio jets and/or nuclear outflow are used to provide important information about the interaction region of the jets/outflow with the interstellar medium (jet/outflow material distribution and dynamics). In order to perform such studies, high angular resolution measurements are fundamental and, in particular, those obtained by using the very long baselines interferometry (VLBI) technique through existing arrays. So far, albeit with a great scientific potential, only a limited number of water megamasers have been studied into detail. Hence, increasing the number of sources investigated and deepening our knowledge on their nature is mandatory to obtain relevant clues on accretion/ejection process in AGN, particularly in the framework of the Unified Model. With this in mind, we have entertained an observational campaign with the VLBA and EVN on a sample of promising AGN hosting bright water megamaser emission. In this talk, we will report on the first results of high-sensitivity, multi-epoch K-band VLBI study of the nuclear region of the LINER megamaser galaxy IC 485. The outcome of our analysis indicate that the maser emission is resolved into two main group of features, spatially distinguished and separated by about 500 km/s, one centered at the systemic velocity of the nuclear region of IC 485 and the other red-shifted. Complemented by recent single-dish measurements, our study suggests that the maser is associated with an edge-on accretion disk in Keplerian rotation, with a north-south orientation, enclosing a mass of $M_{BH} = 1.2 \times 10^7 M_\odot$, consistent with the one expected for a SMBH in a LINER galaxy. The width of the systemic component and an additional tentative feature does not, however, allow us to rule out the hypothesis of jet/outflow maser or a composite (disk+jet) maser origin.

Unveiling fine details of the (giga)maser source in TXS2226-184 with the VLBI

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In nearby and distant active galactic nuclei (AGN), water (mega)masers are associated with i) accretion disks around super-massive black holes (SMBH), and can be used to determine the disk geometry, precise black hole masses, and standard-candles-independent distances to the host galaxy (*disk-masers*); ii) radio jets, where they are either the result of an interaction between the jet(s) and an encroaching molecular cloud, and they provide important information about the evolution of jets and their hotspots (*jet-masers*); iii) nuclear outflows, tracing the velocity and geometry of nuclear winds at < 1 pc from the nucleus, offering a promising means to probe the structure and motion of the clouds predicted by clumpy torus models (*outflow-masers*). All these studies rely on the measurements obtained by VLBI arrays. In this talk, we will report on the main outcome of our recent study, performed with the VLBA and EVN networks, of the water gigamaser in TXS2226-184. Surprisingly, since its discovery in the mid-nineties, this exceptionally luminous source was never been studied into details. Indeed, we measured, for the first time at milliarcsecond resolution, its absolute position, we compared the morphology and characteristics of the maser emission on VLBI scales after about 20 years, and tried to detect its polarized emission. Our analysis indicates an association of the maser emission with a luminous radio knot in the nuclear region of the galaxy, seemingly part of a large scale radio jet, hence supporting a jet/outflow nature of the maser. Due to the uncertainty in the exact location of the SMBH, a different origin related to a disk-maser can, however, still be brought into play. Accordingly, in our presentation we will also outline new results from our multi-frequency radio-continuum EVN observations of the innermost region of TXS2226-184 where a clearer picture of the nuclear individual components of the AGN is obtained and the chance is offered to disentangle between the different proposed scenarios for this intriguing, particularly bright maser source.

Space VLBI for two H_2O MegaMasers

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The RadioAstron Space-VLBI mission has successfully detected extragalactic H_2O MegaMaser (MM) emission regions at space-Earth baselines ranging between 1.4 and 26.7 Earth Diameters (ED). We report on the results for two galaxies, NGC 3079 and NGC 4258, having distinctly different masering environments and excitation conditions.

The H_2O high-brightness maser regions in NGC 3079 form an arc that is offset from the triple components of the Compact Symmetric radio Object (CSO) at the nuclear center. They appear to result from shock excitation of the nuclear ISM and correspond with blue-shifted OH and HI absorption components. The cross-correlation spectrum of NGC 3079 on 2.3 ED and higher space-Earth baselines indicate that the maser emission regions appear extended.

The H_2O MM emission regions in NGC 4258 are confined within a nearly edge-on disk of 0.5 pc surrounding the nuclear AGN with a CSO radio structure. The H_2O emission has been detected with space-Earth baselines up to 26.5 ED, which constitutes a record resolution of 8 micro-arcseconds or a spatial resolution at the galaxy of 60 AU inside the 0.5 pc disk. At the highest resolution the broad multi-component H_2O spectrum breaks up into regularly-spaced individual components. Explaining these components highlights the special conditions of the masering activity inside the accretion disk.

Cosmological studies with VLBI
(Review)

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Current cosmological controversies can only be solved when a sufficient level of precision is achieved by observations. Future all-sky surveys with the next generation of telescopes will offer significantly improved depth and angular resolution with respect to existing observations, opening the so-called "era of precision cosmology". But that era has already started at the radio wavelengths with VLBI. In this talk I will review how VLBI is contributing to some open questions in contemporary cosmology by reaching the largest distances and the smallest scales.

Cosmological QUOKKAS: Using VLBI to make a Hubble Diagram.

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Recently there has been substantial debate around the reliability of cosmological distance measures. Potential sources of systematic error could be influencing the interpretation of results. For this reason, there is a great need for a new and independent distance measure. In this presentation, I will present the 'standard speed-gun' method of measuring distances to blazars which can be seen from 0 ¡ z ¡ 6. The core assumption of the method is that the variability seen in blazars is constrained by the speed of light. This then allows us to calibrate a standard ruler which is then compared with the apparent size; measured with VLBI. We applied this method to the famous nearby source 3C 84 and derived a measurement of the Hubble Constant. This technique has several advantages over other distance measures such as Type Ia supernovae but is currently limited by the sensitivity and cadence of existing VLBI arrays. The Cosmological QUOKKAS program will use the KVN with the Mopra telescope in Australia to measure distances to AGN over a large redshift range. The initial program is somewhat limited, but new arrays such as SKA-VLBI and the ngVLA could potentially allow distance measurements to tens of thousands of sources or more.

J2102+6015: an Intriguing Radio-loud Active Galactic Nucleus in the Early Universe

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The powerful high-redshift quasar J2102+6015 (at $z = 4.575$) may provide useful information for studying supermassive black hole growth, galaxy evolution and feedback in the early Universe. The source has so far been imaged with very long baseline interferometry (VLBI) at 2/8 GHz (S/X) bands only, showing complex compact structure. Its total radio spectrum peaks at ~ 6 GHz in the rest frame. There is no sign of Doppler-boosted jet emission, and the separation of the two major features in its east–west oriented structure spanning ~ 10 milliarcsec does not change significantly on a time scale longer than a decade. However, VLBI astrometric monitoring observations suggest quasi-periodic (~ 3 yr) variation in its absolute position. J2102+6015 is presumably a young radio source with jets misaligned with respect to the line of sight. Here we report on our new high-resolution imaging observations made with the European VLBI Network (EVN) at 5 and 22 GHz frequencies in June 2021, and give an overview of what is currently known about this peculiar distant jetted active galactic nucleus.

VLBI studies with the International LOFAR Telescope *(Review)*

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The International LOFAR Telescope (ILT) has baselines up to 2,000 km with 52 stations spread across Europe, making it capable of sub-arcsecond resolution imaging at MHz frequencies. However, high resolution imaging at low frequencies is technically and logistically challenging: LOFAR's phased-array design, the ionosphere, the lack of suitable calibrator information, and existing software tools all conspire to make it difficult to achieve the highest possible resolution at MHz frequencies. Over the past few years, we have built on our growing understanding of these challenges, relying heavily on techniques from the VLBI community, to design a suitable calibration strategy, which is now implemented in a publicly available pipeline. In the past year this has enabled us to more than double the number of scientific papers published using sub-arcsecond imaging ¡ 200 MHz, including cutting edge work to image the entire 5 square degree field of view of LOFAR at sub-arcsecond resolution. In this talk, I will give an overview of the challenges of high-resolution imaging at low frequencies, how the calibration strategy overcomes these challenges, and summarise the recent science results with a look towards future work.

Cosmic Magnetism with LOFAR

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Radio-loud AGN can be observed throughout the majority of the history of the Universe and are thus excellent beacons for measuring the properties of the cosmic web and their evolution with cosmic time. In this talk, I will highlight recent results from the Low Frequency Array (LOFAR) telescope that use the effect of Faraday rotation to transform our understanding of magnetic fields in the filaments and voids of the cosmic web. The data I will present was obtained as part of the ongoing LOFAR Two-Metre Sky Survey (LoTSS), which recently had its second public data release covering ∼27% of the northern sky. LoTSS provides exceptionally precise Faraday rotation measure (RM) values (δRM$\sim$0.05 rad/m^2), in addition to unrivalled resolution, sensitivity and image fidelity at low frequencies, which facilitates the reliable identification of the host galaxy, and thus the redshift where available. This enabled us to produce a catalogue of RM values (i.e. an RM Grid) across 5,720 deg^2 of sky containing 2,461 sources, 79% of which have redshifts (both spectroscopic and photometric). The combination of precise RM values and their associated redshifts enables us to map the evolution of magnetic fields in the large scale structure with cosmic time, as well as studying the magnetic field properties of sub-classes of AGN such as blazars and radio galaxies.

Elais-N1 field: current International LOFAR sub-arcsecond deep field imaging strategy

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With long intra-continental baselines, the International LOFAR Telescope (ILT) has the potential to instantaneously capture large fields at an angular resolution of a few sub-arcseconds down to tens of MHz. In the ongoing LOFAR Two-metre Sky Survey (LoTSS), three LoTSS Deep Fields, namely Elais-N1 (16:11:00 +55:00:00), Lockman Hole (10:47:00 +58:05:00) and Boötes (14:32:00 +34:30:00) were imaged with core and remote LOFAR stations only, reaching angular resolutions of a few arcseconds (Tasse et al. 2021, Sabater et al. 2021, Williams et al 2021). With the advanced progress in ILT calibration strategies, Sweijen et al. (2022) added and exploited the international station data to obtain a 7.4 deg2 Lockman Hole deep image, pushing the angular resolution from 6" to 0.3". Following this pilot case, with the improved and further-tested calibration and imaging strategies, we present two image products of another deep field: Elais-N1. One is a sub-arcsecond resolution image, and the other is an intermediate image product at a resolution of 1", with their corresponding catalogues provided. The current workflow of making such deep images at both resolutions will be outlined, followed by a brief introduction to the ongoing deep imaging pipeline development. This work validates the current calibration and imaging strategies and explores potential accelerating strategies, inviting the community to explore more deep fields from the LoTSS and opening a new era of ILT as an efficient sub-arcsecond survey machine.

The Accuracy of the JPL X/Ka Celestial Reference Frame

Christopher Jacobs[1]

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The 3rd International Celestial Reference Frame (ICRF-3) provides the practical realization of the IAU's system of angular coordinates on the sky. It is composed of three components: S/X-band (8 GHz), K-band (24 GHz), and X/Ka-band (32 GHz). Since the adoption fo the ICRF-3 in 2018, work has continued at all three bands.

This presentation will evaluate the accuracy of latest X/Ka frame by comparing it to other frames. The accuracy of the original ICRF-3 X/Ka solution was limited by Z-Dipole and quadrupole 2,0 distortions thought to be caused by limited network geometry and troposphere modellng. We will discuss progress towards reducing these distortions below 100 μarcsec from improved network geometry and improved solution strategy. Particular attention will be given to the role of correlations in determining an accurate frame.

Trialling the use of generative adversarial networks for efficient identification of radio frequency interference

Jacob Brooks

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All observations in the radio range of frequencies suffer from some level of contamination from RFI. The impact of this contamination varies with the location and sensitivity of the antenna arrays, though the overall pollution of the spectrum is growing. With developments such as massive satellite networks, even observatories in so-called radio quiet zones will experience significant increases in RFI contamination. Methods of RFI identification must, therefore, become more advanced, ideally without burdening the astronomer with a greater need for intervention. The field of machine learning has seen huge leaps forward in the last decade, and many studies utilising these techniques for various applications in radio astronomy have shown that the machine learning approach has tremendous potential. I will present work on using the generative adversarial network architecture for the purposes of RFI identification. The network has been trained entirely on manually flagged e-MERLIN observations and early results show promise. I will discuss the benefits of this technique over existing automatic flagging methods, along with some of the hurdles that must be overcome.

ngDIFMAP: new generation DIFMAP for Modelfitting Interferometric Data and Estimating Variances, Biases and Correlations

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Real interferometric datasets are noisy and generally lack optimal UV coverage, making interpretation of subtleties in source structure difficult. Fitting models to the complex visibilities or other observables in the UV plane is generally preferred as a solution when one needs the most accurate description of the true source properties. We present a new generation of DIFMAP (**ngDIFMAP**) that adds modelfitting of interferometric closure quantities with a global optimization algorithm, which allows for much greater model complexity as well as more accurate estimates of model parameter errors. Additional functionality allows one to empirically evaluate the ramifications of amplitude and phase errors, and loss of UV coverage on estimated parameters, in terms of biases and variances of and correlations between parameters. We find that some parameters are always correlated, and antenna errors can cause significant increase in variance and bias for all parameters for a multi-Gaussian model, where we provide apt prescriptions to quote the final fit results. We demonstrate the use of **ngDIFMAP** to suitably characterize VLBI observations of the "changing-look" AGN 1ES 1927+654, where we find evidence for subtle but real changes in the parsec-scale resolved radio emission. The **ngDIFMAP** tool is a pathway to understanding noisy interferometric data more accurately than ever before.

Multiscale VLBI imaging

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Reconstructing images from very long baseline interferometry (VLBI) data with sparse sampling of the Fourier domain (uv-coverage) constitutes an ill-posed deconvolution problem. It requires application of robust algorithms maximizing the information extraction from all of the sampled spatial scales and minimizing the influence of the unsampled scales on image quality. We present novel multiscale wavelet deconvolution algorithms for imaging sparsely sampled interferometric data. These new ideas are based on a novel, specially designed wavelet dictionary and hard image thresholding in the spirit of compressive sensing. Compressing various spatial features of the true sky brightness distribution by various scales provides a powerful way to analyse the uv-coverage during imaging and improving the seperation between covered features and features introduced by gaps in the uv-coverage. We demonstrate the stability of our novel algorithmic ideas and benchmark their performance against image reconstructions made with CLEAN and Regularized Maximum-Likelihood (RML) methods using synthetic data. The comparison shows that multiscalar approaches match the superresolution achieved by the RML reconstructions and surpass the sensitivity to extended emission reached by CLEAN. Moreover, the imaging is largely data-driven reducing the human induced bias during the imaging procedure. Finally, we present some applications to observed data sets of various instruments revealing image features with unmatched resolution and quality.

The Readiness of EVN Telescopes for the SKA-VLBI Era

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The SKA is currently under construction and offers the possibility for ultra-precise astrometry; an order of magnitude improvement in the precision and also the frequency range at which astrometry can be performed today. This will allow for the application of astrometric methods to a much wider set of targets and science cases. Over the last few years the community has been working hard to ensure the SKA design includes the capability to enable multiple simultaneous tied-array beams, which is a crucial technology to deliver ultra-precise astrometry (and improve survey capabilities).

The MultiView methods have demonstrated, with an increasing number of astrometric measurements, outstanding performance, reaching the thermal noise limit of current VLBI networks, as predicted by our error analysis. We estimate an order of magnitude improvement for SKA-VLBI, assuming an upgraded network of antennas that match the SKA capabilities. This is predicated on the sensitivity improvement from the increased collecting area and the quasi-perfect compensation of systematic atmospheric effects, as provided by MultiView. We identify multiple-beam technology, on large telescopes and connected arrays, as the crucial missing component and here will make recommendations for the upgrade path of the partner EVN (and other) telescopes.

Unveiling the Origin of Radio Emission in Nearby Low-Luminosity AGNs with VLBI

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The origin of the radio emission in LLAGNs has been a matter of debate for a long time. It is not well understood whether the emission is caused by star formation in the host galaxy or by black hole activity of the active galactic nuclei (AGN). LLAGNs typically show compact radio structures, and it is of fundamental importance to resolve the nuclear emission with a high spatial resolution to investigate the origin of the radio emission. The best way to study nuclear accretion is by observing nearby galaxies. The proximity enables high spatial resolution and high sensitivity observations, allowing the detection of sources of lower luminosity. To perform a study of the radio properties of LLAGNs on sub-parsec scales, we selected 36 nearby LLAGNs from the Legacy eMERLIN Multi-band Imaging of Nearby Galaxies survey (LeMMINGs) and observed them with e-EVN + e-MERLIN and VLBA at 5 GHz. More than half of the sources were detected. In this talk, we report for the first time on the detection result of a large sample of LLAGNs with EVN and VLBA. The nature of pc-scale radio emission and the structural changes associated with radio loudness in LLAGNs will be discussed.

The power of low luminosity active galactic nuclei: PARSEC view

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It is possible that most galaxies host a black hole at the centre, most of the time this being in a relatively quiescent state. The so-called low luminosity Active Galactic Nuclei are characteristic of this phase. These objects represent the vast majority of the active galactic nuclei (AGN) population in the near universe, and still the least conforming class with the standard AGN scenario. Their low luminosity is at odds with their often very high black hole masses and powerful jets. I will present the challenges that parsec-scale observations across the electromagnetic spectrum of some of the nearest ones impose on the true nature of their emission, their transition from the most luminous to the feeble ones, and their accretion power. The strict limits imposed by these observations on their accretion power are confronted with the high mechanical energy inferred for their jets. Possible scenarios for these nuclei including the extraction of power form the black hole spin are discussed.

Exploring the disk-jet connection in NGC 315

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Observational and theoretical evidences suggest that hot accretion flows are able to power the relativistic jets launched by AGN. Depending on their magnetization level, the hot accretion flows can be SANE (Standard And Normal Evolution) disks or MAD (Magnetically Arrested Disks). The nature of the accretion disk is closely related to some properties of the jets at their base, such as the extent of the acceleration and collimation region (ACR), which can be probed through Very-Long-Baseline Interferometry (VLBI) observations. In this framework, we present our work on NGC 315, a nearby ($z = 0.0165$) giant Fanaroff-Riley I radio galaxy whose jet can be imaged with a spatial resolution down to only ~ 100 Schwarzschild radii at 86 GHz. We observe the ACR to extend up to ~ 0.6 de-projected parsec from the central core, with the jet undergoing a fast acceleration that we theoretically reconcile with a magnetically driven one. We perform spectral studies using simultaneous observations at 22 and 43 GHz and we find evidence of an unexpected spectral behaviour, with very steep spectral index values $\alpha \sim -1.5$ ($S_\nu \propto \nu^\alpha$) along the collimating region. From the extension of the ACR, the theoretical model used predicts the black hole of NGC 315 to be fast rotating and the dimensionless magnetic flux threading the accretion disk to be close to the expected MAD saturation level of $\phi_{\rm BH} \sim 50$. Using a new formalism based on the core-shift effect, we model the magnetic field downstream a quasi-parabolic, accelerating jet and we extrapolate it up to the jet base obtaining magnetic strengths consistent with the expectation from a MAD. Our results suggest that the accretion disk in NGC 315 may have reached the magnetically arrested state.

Feedback from radio AGN: the case of 4C31.04

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The interplay between the nuclear activity and the interstellar medium (ISM) of galaxies plays an important role in their evolution: the gas accreting onto the dormant supermassive black hole turns it into an active galactic nucleus (AGN) and the ensuing activity is believed to starve the host galaxy of the fuel needed to form stars. The contribution of radio-loud AGN to this feedback effect is yet to be well understood. In order to understand the impact of radio AGN, we need to study the jet-ISM interaction in detail in sources covering a wide range of parameters such as age/morphology, radio power. In this context, I will present a detailed study of cold atomic gas (HI) in the nuclear region of a very young (5000 years old), powerful radio source 4C31.04. Our deep Global VLBI observations reveal the presence of HI in the form of a cocoon generated by the expanding radio jets, as predicted by numerical simulations. This study is another step forward in quantifying the impact of radio jets on the ambient ISM and thereby the evolution of their host galaxies.

The collimation and acceleration zone of double-sided AGN jets

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Besides decades of observational studies the formation and collimation of relativistic jets in AGN is not yet fully understood. Since recently, the vast improvements of VLBI in terms of sensitivity and resolution allow a direct comparison of observations of the jet collimation and acceleration region with predictions from GRMHD simulations. Based on this comparison the typically observed change from a confined, accelerating jet with a parabolic geometry to a freely expanding jet with a conical geometry at distances of 10^4–$10^6 R_\mathrm{S}$ (*Schwarzschild radii*) is in accordance with theoretical expectations for the transition region from a magnetically to a kinetically dominated jet. On the basis of the nearby LINER NGC 1052 I will discuss the unusual cylindrical geometry and continuum spectrum of a double-sided jet with multi-frequency VLBI observations. I will focus on observational frequencies above 15 GHz to minimize the impact of the optically thick, absorbing torus on the collimation profile and continuum spectrum. By comparison with GRMHD simulations this cylindrical structure can be explained by the contribution from a disk wind, which is expected to be reduced with increasing frequency. Indeed, our measurements at millimeter wavelengths suggest a deviation from the cylindrical profile at distances of a few hundred R_S closer to the central engine, implying a second geometry break.