Proceedings of the 16th European VLBI Network Symposium
Ros, E., Benke, P., Dzib, S., Rottmann, I., & Zensus, J.A. (eds.)
September 2nd-6th 2024, Bonn, Germany

M2FINDERS: Mapping Magnetic Fields with Interferometry down to Event Horizon Scales

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Abstract. Active Galactic Nuclei are the most extreme sources of power in the Universe, outshining their entire host galaxies. The Event Horizon Telescope collaboration has successfully imaged supermassive black holes in Messier 87 and Sagittarius A⋆ at event horizon scales, confirming theoretical predictions from General Relativity. However, to determine the physical properties of these black holes, precise information about the magnetic field near the event horizon is crucial. The M2FINDERS project aims to address this challenge by mapping magnetic fields at distances smaller than a thousand gravitational radii. M2FINDERS is approaching the problem using multi-frequency polarimetric VLBI measurements, and novel image analysis and relativistic flow modeling techniques. The plan is to place strong constraints on the magnetic field near the event horizon, providing evidence for the existence of black holes and their event horizons. This paper presents progress on data analysis and interpretation.

1. Introduction

The majority of galaxies, including our own, are home to supermassive black holes (SMBHs) with masses reaching up to several times that of the Sun (Heckman & Best 2014; Kormendy & Ho 2013; Fabian & Lasenby 2015). In active galactic nuclei (AGN), these black holes emit a significant amount of energy through their rotational and accretion processes, resulting in the production of non-thermal radiation and kinetic flux in relativistic jets. A substantial body of research has been conducted into the relationship between jet properties and black hole physics, with a particular focus on the role of magnetic fields in the vicinity of the event horizon (Blandford & Znajek 1977; Narayan et al. 2003; Tchekhovskoy et al. 2011; Lasota et al. 2014).

To advance our comprehension of these systems, it is imperative to conduct meticulous observational investigations of magnetic fields at scales below 1000 gravitational radii (r_g), which is equivalent to approximately 0.05 parsec or less than a milliarcsecond in angular resolution (for typical blazar cosmological distances). At present, such high-resolution imaging is only feasible in the radio band through the use of very long baseline interferometry (VLBI) at frequencies exceeding 15 GHz, with the upper limit reaching 230 GHz. This capability was notably demonstrated by the Event Horizon Telescope's (EHT) imaging of Messier 87 (M 87; EHT Collaboration 2019a) and Sagittarius A⋆ (Sgr A⋆; EHT Collaboration 2022).

While the detection of gravitational waves (Abbott et al. 2016) and infrared observations of hot-spot motions in the vicinity of Sgr A⋆ (Abuter et al. 2018, 2020) have provided further evidence for black holes, more data are needed to definitively confirm their existence and properties. The EHT project aims to significantly increase the dynamic range of imaging, which is essential for testing alternative theories such as gravastars or collapsed polymers (Mizuno et al. 2018; Olivares et al. 2020). The integration of EHT imaging with magnetic field measurements near

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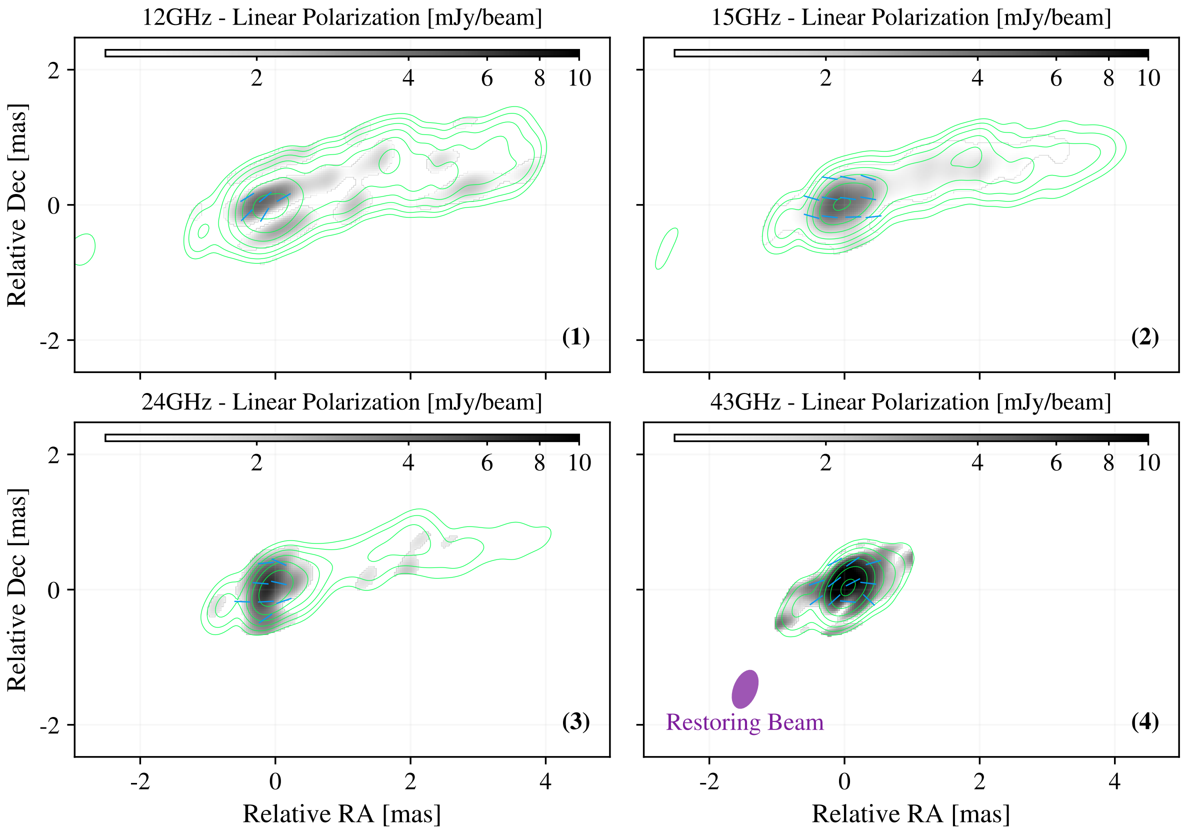

Fig. 1. Cyg A Stokes I contours superposed on the linear polarisation VLBA images for the frequencies 12, 15, 24, and 43 GHz (Livingston et al. in prep.).

the event horizon is a promising way to confirm the existence of black holes.

Recent observations have indicated the presence of magnetic fields exceeding 10 000 G near SMBHs, as evidenced by high levels of polarisation (Johnson et al. 2015), significant Faraday rotation (Martí-Vidal et al.2015a), and extreme brightness temperatures (Gómez et al. 2016; Kovalev et al. 2016). It is important to obtain precise measurements close to the black hole event horizon in order to address a number of key questions. These include determining the maximum strength and structure of magnetic fields, their radial dependence, and their effect on energy transport in active galactic nuclei.

The combination of gravitational wave data (Chirenti & Rezzolla 2016) with EHT findings (Sakai et al. 2014; Falcke 2017; EHT Collaboration 2019a–2019f) is anticipated to provide a robust framework for investigating the physical nature of black holes, which represents the primary objective of M2FINDERS. In particular, polarimetric VLBI imaging across 15–230 GHz can effectively probe magnetic fields by mapping linear polarisation (Leppänen et al. 1995; Gómez et al. 2016), as well as Faraday rotation (Gabuzda et al. 2015, 2017). Furthermore, the effects of day rotation (Gabuzda et al. 2015, 2017) and synchrotron turnover frequencies (Lobanov 1998a; Fromm et al. 2013) must be considered.

It is of importance to enhance the imaging sensitivity, polarisation calibration and astrometric accuracy, particularly through techniques such as source-frequency phase referencing (SFPR; Rioja et al., 2015). The extension of multi-frequency capabilities to telescopes such as the Effelsberg antenna could facilitate core shift measurements with an accuracy of approximately 10 microarcseconds, thereby significantly advancing our understanding of jet structures.

Analytical and numerical models (Perucho et al. 2006; Porth et al. 2019) provide a robust basis for interpreting observational data, facilitating detailed investigations of magnetic fields and plasma densities in AGN jets. The integration of advanced observational techniques and modeling holds the potential to transform our understanding of SMBHs, offering the most reliable evidence of their existence and physical properties.

The research addressed by the M2FINDERS is structured around three primary areas: (i) VLBI measurements of magnetic fields, (ii) the development of novel observational techniques, and (iii) physical modeling of these observations. The magnetic field surrounding accreting SMBHs is subject to regulation by disk processes and can attain strengths of up to 10 000 G, exhibiting a decline in intensity with increasing radius. In contrast, horizonless objects like gravastars may display stronger, dipoledominated fields that decrease as the inverse of the radius (Narayan et al. 2003; Mazur & Mottola, 2001, 2004).

2. Magnetic Field Measurements

This area investigates the magnetic fields around SMBHs with high precision, focusing on their strength, structure, and influence on AGN dynamics, which are the core objectives of M2FINDERS. Observations target a carefully selected sample of AGN, including, amongst others, 3C 273, BL Lac, M 87, and Sgr A*. Data is collected using the Very Long Baseline Array (VLBA), the Global Millimeter VLBI Array (GMVA), and the EHT, spanning frequencies from 15 GHz to 230 GHz.

Initial results include robust estimates of magnetic field strengths near the event horizon, with values around 10^5 Gauss. Observations of M 87 reveal a ring-like structure corresponding to its black hole shadow, with polarimetric imaging showing toroidal magnetic field configurations consistent with theoretical spine-sheath models. The high brightness temperatures and Faraday rotation measures observed in these sources provide additional constraints on magnetic field properties.

In addition, multi-wavelength VLBA observations of Cygnus A (Cyg A) have revealed for the first time clear signs of polarisation near the core region (see Fig. 1), a unique finding for this object (J. Livingston et al. in prep.). Such observations can also be used to study the Faraday rotation and the intrinsic EVPA, and to constrain the magnetic field drivers of each source. Finally, the magnetic field strengths of the very compact quasar NRAO 530 have been estimated for different observed frequencies; see Fig. 2. The observations were obtained with the VLBA, GMVA and EHT arrays and were made during the 2017 EHT campaign. The observations were made in five bands centred on the frequencies 15.4, 22.2, 43.12, 86.2 and 227.1 GHz. Some results will also be published together with the EHT collaboration.

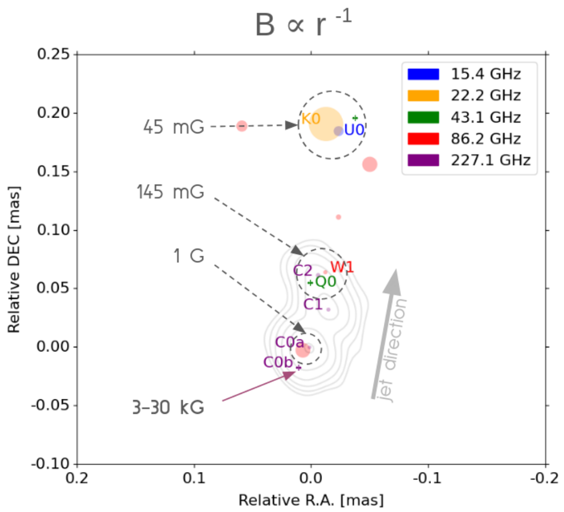

Fig. 2. Stokes I contours and model fit components of very compact Quasar NRAO 530 for different observed frequencies. The magnetic field strength estimates are derived from the first-ever core-shift measurements at frequencies ranging between 15 GHz and 230 GHz for this source. The estimate of $(3-30)$ kG is calculated assuming that component C0b is at a distance of $5\,r_g$ from the SMBH and that the SMBH has a mass of $(2-20)\times 10^8$ $M_\odot$ (P.I.: M. Lisakov).

3. Interferometric Techniques

This research focuses on developing the technological and methodological aspects of the experimental measurements and data analysis required for the VLBI observations from the previous subsection. The technological aspects under research involve three aspects: (i) imaging software developments, (ii) improving the observation capabilities, and (iii) commissioning new receivers to enhance future VLBI observations.

3.1. Software Development

Within the M2FINDER project, innovative imaging algorithms have been developed. These are DoG-HiT (Müeller & Lobanov 2022), MOEA/D (Müeller et al. 2023), and Bayesian self-calibration and imaging method contained in the `Resolve` software (Kim et al. 2024). These new software packages outperform traditional methods by reconstructing high-fidelity images from sparse VLBI datasets (see for example Fig. 3). These techniques enable the resolution of dynamic and polarimetric structures, enhancing the interpretation of AGN jet morphology.

3.2. New Observation Techniques

The frequency phase transfer (FPT) technique enables, through simultaneous multi-frequency observations, to calibrate fast phase fluctuations at higher frequencies using the less challenging phase corrections of lower frequencies (Dodson et al. 2023). It has been successfully implemented in the Korean VLBI Network (KVN), and it is now being expanded to other VLBI arrays, such as the VLBI Exploration of Radio Astrometry (VERA) from Japan, and other VLBI stations around the world.

M2FINDERS team members have recently participated in the first simultaneous multi-frequency VLBI observations to test the FTP technique on baselines longer than 8000 km. The observations included the combined KVN and VERA Array (KaVA) as well as the Yebes telescope in Spain (see the top panel of Fig. 4). Promising results have been obtained with the first data analysis (see bottom panel of Fig. 4). The results forecast the importance that the FPT technique could play on mm-VLBI observations and show the importance of developing multi-frequency receivers for VLBI stations.

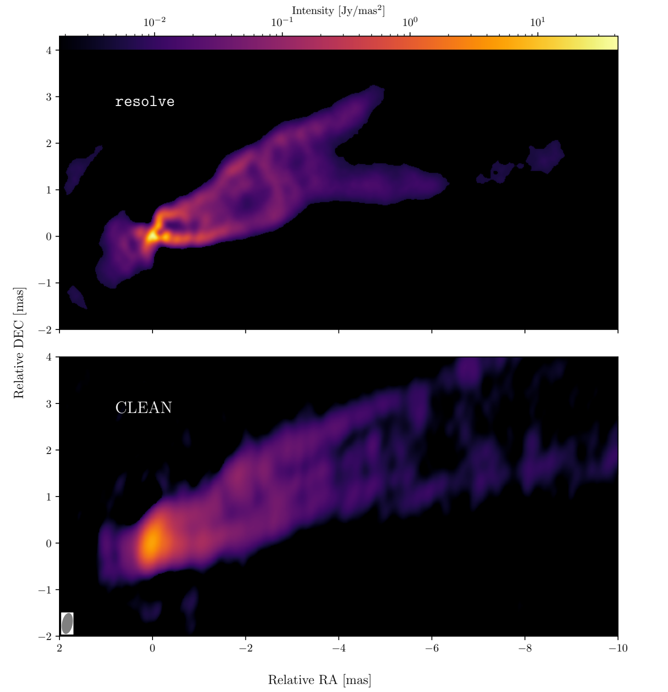

Fig. 3. Image comparison between resolve reconstruction by Bayesian self-calibration and imaging (*Top-panel*) and CLEAN reconstruction by conventional CLEAN self-calibration (*Bottom-panel*). Both images are for M 87 VLBA data at 43 GHz. Figure from Kim et al. (2024).

3.3. Multi-Frequency Receivers

Improving the quality of the opacity probes via the core-shift measurements becomes possible through VLBI observations with a three-band 22/43/86 GHz receiver system (Han et al. 2017). Such a system will be installed (independent of M2FINDERS funding) at the Effelsberg 100m telescope and then used in joint observations with the KVN, the Italian VLBI Network, and the Yebes telescope in Spain, increasing by one order of magnitude the accuracy of core shift measurements using the source-frequency phase-referencing technique (Rioja et al. 2011, 2015, 2020, Jung et al. 2015, Dodson et al. 2017) implemented at the KVN. Note that the 100-m Effelsberg telescope provides sufficient sensitivity for this goal, owing to its large collecting area.

4. Physical Modelling

This area of work is developing and applying a set of tools for detailed physical modeling of the observed total intensity and polarised emission. The main aim here is to provide the most accurate estimates of the strength and three-dimensional structure of the magnetic field from the observational measurements as described in Sect. 2 This work will build on our long-term, continued effort in the analysis and interpretation of VLBI observations of AGN jets (e.g., Zensus et al. 1995; Lobanov & Zensus 1999, 2001; Perucho et al. 2006; Fromm et al. 2016, 2019)

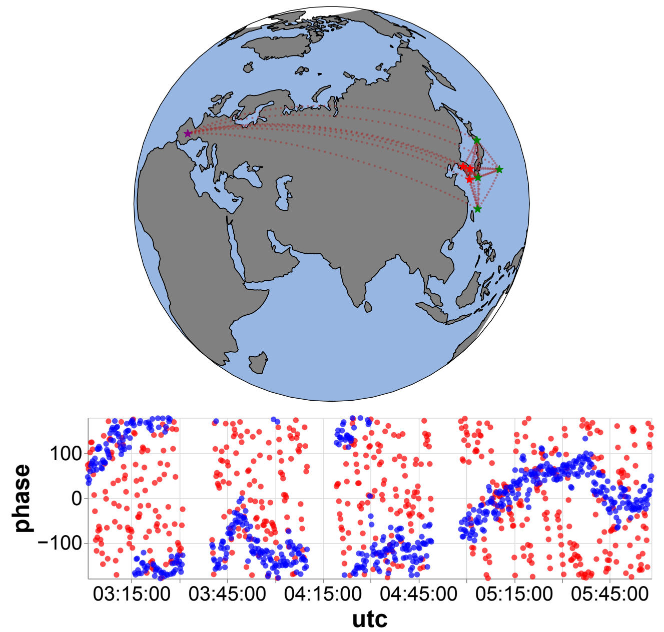

Fig. 4. *Top:* The KaVA-Yebes array. *Bottom:* Example of the visibility phases before (red dots) and after (blue dots) FPT corrections. Figures from Zhao et al. (in prep.)

and it will focus on improving robustness and accuracy of magnetic field estimates obtained from the core shift measurements and turnover frequency mapping. This research will provide a robust framework for a physical interpretation of the entire set of measurements resulting from the M2FINDERS program. The work will be focused on three major tasks described below.

4.1. Magnetic fields across scales

Multiwavelength VLBI observations of AGN sources, including 230 GHz observations with the Event Horizon Telescope and 86 GHz GMVA observations, allow us to model the magnetic fields on scales from tens of parsecs all the way to the near vicinity of the central black hole; see Fig. 5. Rapid decay of the magnetic field strength with distance may be explained by the jet acceleration or strong dissipation of the magnetic energy (J. Röder et al. submitted to A&A).

4.2. Modeling jet formation region

We use a complete model of radiative transfer coupled with ray-tracing in curved spacetimes around black holes to investigate polarised images of jets very close to the central supermassive black hole. The produced synthetic images are used to understand the impact of magnetic field geometry, spacetime curvature, and Faraday effects on the images of jet formation regions (Saurabh et al. in prep). For example, Fig. 6 shows a parabolic jet model for two magnetic field configurations.

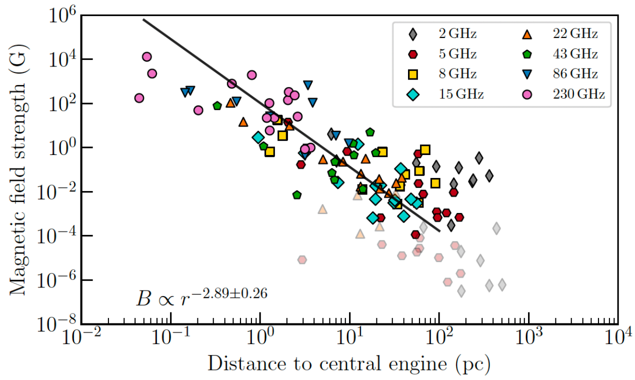

Fig. 5. Magnetic field estimates obtained from VLBI observations as a function of the distance to the central engine. Figure from J. Röder et al. (submitted).

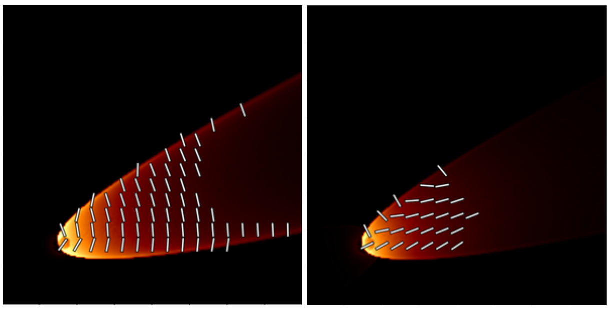

Fig. 6. Model of a parabolic jet forming around a Kerr black hole for different magnetic field configurations. Figure from Saurabh et al. (in prep).

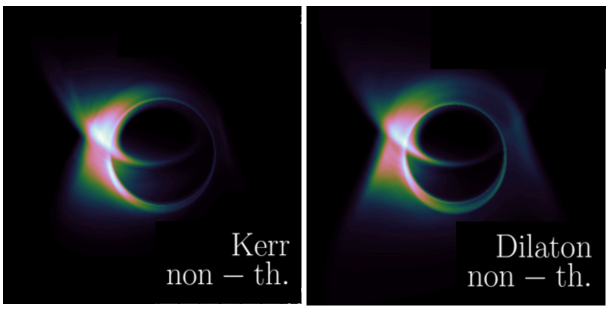

Fig. 7. Comparison between simulated non-thermal Kerr and dilaton black-holes. Figure from Röder et al. (2023).

4.3. Exotic spacetimes?

Exotic objects (wormholes, naked singularities, boson stars, non-Kerr black holes, ...) are considered as alternative candidates for compact masses at the centre of galaxies. Since current ultra-high angular resolution observations, including the EHT, are still insufficient to unambiguously constrain the models of such objects, further theoretical investigations of their properties (accretion models, particle distribution functions, and characterisation of the space-time geometry) are required. The signatures of such objects and their implications for jet formation and magnetic fields are also being studied within M2FINDERS. For example, Röder et al. (2023) carried out 3D GRMHD simulations of Kerr and dilaton black holes (see Fig. 7) and found a wider jet opening angle and higher magnetisation in the Kerr spacetime.

5. Conclusion

The M2FINDERS project significantly advances the study of SMBHs and their magnetic environments by combining observational, technological and theoretical approaches. The results of the project provide strong evidence for the existence of magnetic fields near SMBH event horizons, contributing to our understanding of accretion and jet formation mechanisms. Future work will focus on integrating mm-VLBI observations with next-generation instruments to refine magnetic field maps and explore their role in AGN energetics.

Acknowledgements. This work is part of the M2FINDERS project which has received funding from the European Research Council (ERC) under the European Union's Horizon 2020 Research and Innovation Programme (grant agreement No 101018682). V.B., E.R., and J.A.Z. also acknowledge support from the by the Deutsche Forschungsgemeinschaft (DFG, German Research Foundation)- grant 443220636, (FOR5195: Relativistic Jets in Active Galaxies). The VLBA is a facility of the National Science Foundation operated under cooperative agreement by Associated Universities, Inc. APEX is a collaboration between the Max-Planck-Institut für Radioastronomie (Germany), ESO, and the Onsala Space Observatory (Sweden). Some results are based on observations with the 100-m telescope of the MPIfR (Max-Planck-Institut für Radioastronomie) at Effelsberg. This research has made use of data obtained with the Global Millimeter VLBI Array (GMVA), which consists of telescopes operated by the MPIfR, IRAM, Onsala, Metsähovi, Yebes, the Korean VLBI Network, the Greenland Telescope, the Green Bank Observatory (GBT) and the Very Long Baseline Array (VLBA). We are grateful to the staff of the Korean VLBI Network (KVN) who helped to operate the array and to correlate some data presented here. The KVN and a high-performance computing cluster are facilities operated by the KASI (Korea Astronomy and Space Science Institute). The KVN observations and correlations are supported through the high-speed network connections among the KVN sites provided by the KREONET (Korea Research Environment Open NETwork), which is managed and operated by the KISTI (Korea Institute of Science and Technology Information). Some data presented in this work made use of the Swinburne University of Technology software correlator, developed as part of the Australian Major National Research Facilities Programme and operated under licence.

References

Abbott, B. P., Abbott, R., Abbott, T. D., et al. 2016, Phys. Rev. Lett., 116, 061102
Abuter, R., Amorim, A., Anugu, N., et al. 2018, A&A, 615, L15
Abuter, R., Amorim, A., Bauböck, M., et al. 2020, A&A, 636, L5
Blandford, R. D., & Znajek, R. L. 1977, MNRAS, 179, 433

Chirenti, C., & Rezzolla, L. 2016, Phys. Rev. D, 94, 084016
Dodson, R., Rioja, M. J., Jung, T., et al. 2017, NAR, 79, 85
Dodson, R., Rioja, M. J., Jung, T., et al. 2023, Radio Astronomy with Multiband Receivers and Frequency Phase Transfer: Scientific Perspectives, arXiv:2306.04516
Event Horizon Telescope Collaboration, Akiyama, K., Alberdi, A., et al. 2019a, ApJ, 875, L1
Event Horizon Telescope Collaboration, Akiyama, K., Alberdi, A., et al. 2019b, ApJ, 875, L2
Event Horizon Telescope Collaboration, Akiyama, K., Alberdi, A., et al. 2019c, ApJ, 875, L3
Event Horizon Telescope Collaboration, Akiyama, K., Alberdi, A., et al. 2019d, ApJ, 875, L4
Event Horizon Telescope Collaboration, Akiyama, K., Alberdi, A., et al. 2019e, ApJ, 875, L5
Event Horizon Telescope Collaboration, Akiyama, K., Alberdi, A., et al. 2019f, ApJ, 875, L6
Event Horizon Telescope Collaboration, Akiyama, K., Algaba, J. C., et al. 2022, ApJL, 930, L12
Falcke, H. 2017, JPhCS, 942, 012001
Fabian, A. C., & Lasenby, A. N. 2015, De Gruyter Studies in Math. Phys., 28, 7
Fromm, C. M., Ros, E., Perucho, M., et al. 2013, A&A, 557, A105
Fromm, C. M., Perucho, M., Ros, E., et al. 2016, A&A, 588, A101
Fromm, C. M., Perucho, M., Mimica, P., et al. 2019, A&A, 629, A4
Gabuzda, D. C., Knuettel, S., & Reardon, B. 2015, MNRAS, 450, 2441
Gabuzda, D. C., Roche, N., Kirwan, A., et al. 2017, MNRAS, 472, 1792
Gómez, J. L., Lobanov, A. P., Bruni, G., et al. 2016, ApJ, 817, 96
Han, J. L., Manchester, R. N., van Straten, W., et al. 2017, JIMTW, 38, 1487
Heckman, T. M., & Best, P. N. 2014, ARA&A, 52, 589
Johnson, M. D., Fish, V. L., Doeleman, S. S., et al. 2015, Science, 350, 1242
Jung, T., Sohn, B. W., Byun, D. Y., et al. 2015, JKAS, 48, 277
Kim, J.-S., Krichbaum, T. P., Bach, U., et al. 2024, A&A, 690, A129
Kormendy, J., & Ho, L. C. 2013, ARA&A, 51, 511
Kovalev, Y. Y., Kardashev, N. S., Kellermann, K. I., et al. 2016, ApJ, 820, L9
Lasota, J.-P., Gourgoulhon, E., & Abramowicz, M. A. 2014, Phys. Rev. D, 89, 024041
Leppänen, K., Zensus, J. A., & Diamond, P. J. 1995, AJ, 110, 2479
Lobanov, A. P. 1998a, A&AS, 132, 261
Lobanov, A. P., & Zensus, J. A. 1999, ApJ, 521, 509
Lobanov, A. P., & Zensus, J. A. 2001, Science, 294, 128
Martí-Vidal, I., Vlemmings, W. H. T., & Martí, J. 2015a, Science, 348, 311
Mazur, P., & Mottola, E. 2001, Phys. Rev. D, 64, 104022
Mazur, P., & Mottola, E. 2004, PNAS, 101, 9495
Mizuno, Y., Younsi, Z., Fromm, C. M., et al. 2018, Nat. Astron., 2, 585
Müller, H., & Lobanov, A. P. 2022, A&A, 666, A137
Müller, H., Fromm, C. M., Porth, O., et al. 2023, A&A, 675, A60
Narayan, R., Igumenshchev, I. V., & Abramowicz, M. A. 2003, PASJ, 55, L69
Olivares, H., Wielgus, M., Vos, J., et al. 2020, MNRAS, 497, 521
Perucho, M., Lobanov, A. P., Martí, J.-M., & Hardee, P. E. 2006, A&A, 456, 493
Porth, O., Chatterjee, K., Narayan, R., et al. 2019, ApJS, 243, 26
Rioja, M. J. & Dodson, R. 2011, AJ 141, 144
Rioja, M. J., Dodson, R., Jung, T., & Sohn, B. W. 2015, AJ, 150, 202
Rioja, M. J. & Dodson, R. 2020, A&ARv 28, 6
Röder, J., Perucho, M., Wagner, A. Y., et al. 2023, A&A, 671, A143
Sakai, N., Saida, H., Tamaki, T., & Naruko, A. 2014, Phys. Rev. D, 90, 104013
Tchekhovskoy, A., Narayan, R., & McKinney, J. C. 2011, MNRAS, 418, L79
Zensus, J. A., Cohen, M. H., & Unwin, S. C. 1995, ApJ, 443, 35