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STUDIES OF TYPE 2 AGNS BELOW SPATIALLY RESOLVED SCALES: THE CASE FOR ULTRAVIOLET POLARIMETRY

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Abstract. Polarimetry (and ultraviolet – UV – polarimetry in particular) has proven to be one of the most resourceful observational method to constrain the multi-scale geometry and composition of Active Galactic Nuclei (AGNs). Because of its vectorial nature, the polarization of the emitted, scattered or absorbed light is independent of the size of the source region. It allows to study objects that otherwise remain spatially unresolved even to modern telescopes or that can be hidden behind absorbing material. UV polarimetry was at its peak in the 90's, but it ended in the early 2000s when the last space-based far-UV polarimeter instrument was decommissioned in 2002. Here, we present how AGN polarimetry, using 20+ years old HST/FOC archival data used in the context of a multi-wavelength analysis, allows to precisely study the physical process occurring in the (sub)parsec-scale regions of NGC 1068, one of those complex sources. This work aims to highlight the needs for future polarimetric instruments in the UV band.

Keywords: active galactic nuclei, ultraviolet, polarization

1 Introduction

Polarimetry has proven to be one of the most resourceful observational methods in astronomy (Hildebrand 2005; Hough 2006). From stars to planets, supernovae remnants to gamma-ray bursts, polarimetry has brought a wealth of information about the geometry and composition of cosmic sources, including magnetic field intensity and topology in both small- and large-scale structures. However, it is probably the field of active galactic nuclei (AGNs) that polarimetry has contributed the most (Marin 2019, and references therein), starting with the proposition of a unified model for AGNs from optical and ultraviolet (UV) polarimetry (Antonucci & Miller 1985), followed by the uncovering of a near-infrared (NIR) polarized signature ascribed to an accretion disk spectrum in quasars (Kishimoto et al. 2008), or, most recently, the dichotomy of radio-loud and radio-quiet quasars in far-infrared (FIR) polarimetry (López Rodríguez 2023).

The Hubble Space Telescope (HST) was the first major space telescope to reveal the near, mid and far UV spectrum of the sky, though other UV instruments have flown on smaller observatories such as GALEX, as well as sounding rockets and the space shuttles (Linsky 2018). Among the original instruments aboard the HST, the Faint Object Camera (FOC) was an incredible device. It consisted of a long-focal-ratio, photon-counting imager capable of taking high-resolution images in the wavelength range 1150 - 6500 Å. When corrected by COSTAR, the field-of-view (FoV) and pixel size of the f/96 camera were $7'' \times 7''$ and $0.014'' \times 0.014''$, respectively. But, most importantly, it was a polarimeter. The huge spatial resolution offered by the FOC, coupled to the very low instrumental polarization and excellent polarizing efficiencies of the polarizers ($\sim 92\%$) made the FOC a unique instrument, the first to take UV polarimetric images in space. The FOC remained in operation from 1990 to 2002, when it was replaced by the Advanced Camera for Surveys (ACS) during Servicing Mission 3B (March 7, 2002).

However promising the FOC instrument was to achieve great discoveries in the field of AGNs, $\sim 19\%$ of the AGN proposals in the FOC archives lack any exploitation (5/26 AGNs observed with the FOC were never published). The FOC archives underwent their last calibration in 2006, benefiting from 15 years of calibration data with HST as well as 11 years with COSTAR. Along with 20 years of improvement of imaging reduction and analysis, we propose in Barnouin et al. (2023) a new reduction pipeline in order to perform a rigorous, systematically complete and consistent re-analysis of all raw HST imaging polarimetric AGN observations from the FOC in the HST archive to enable science deferred or unachieved by many approved programs. This pipeline allows us to revamp the last ever acquired UV polarization maps of AGNs, as seen in Fig. 1.

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2 UV polarization of AGNs

AGNs are compact yet powerful engines located near the center of their host galaxy. According to the unified model for AGNs (Antonucci & Miller 1985), a central supermassive black hole (SMBH) accrete matter through an optically thick, geometrically thin disk. Such accretion flow radiates as a black body with peak luminosity in the UV band (the *Big Blue Bump*). The accretion disk is surrounded by both a region responsible for the emission of the broad lines in the optical spectrum and by a clumpy torus made of cold gas and dust situated along the same plane, and by a pair of bi-polar ionized outflows on its rotation axis. With this layout, the innermost parts of the AGN (the SMBH, its accretion disk and the broad emission line region) are obscured by the dusty torus for an observer situated on the plane of the disk (a type 2 view), but visible on the polar axis (type 1). This is where polarimetry, most specifically UV-polarimetry, become an invaluable tool. In type 2 AGNs, the obscured core illuminates the polar outflows which scatters the emission onto the observer's line of sight. This periscopic view above the dusty torus enables to probe the innermost regions of the AGN. The host galaxy, whose starlight dilutes the observed AGN polarization, has low stellar contribution in the UV band where the AGN luminosity peaks, reducing greatly contamination from unpolarized surrounding sources.

Ground based optical to near-UV spectropolarimetry greatly improved our understanding of a wide range of AGNs by probing nuclei down to unresolved scales. It brought together type 1 and type 2 AGNs by uncovering the characteristics of hidden type 1 AGNs in the polarized flux of type 2 AGNs, advocating for a difference in viewing angle explained by the system's asymmetric geometry, a pillar of the unified model for AGNs (Antonucci & Miller 1985). Imaging UV polarimetry add to spectropolarimetry a spatial context for the observed polarization. Assuming single scattering of a central illuminating point source (the nucleus) onto a ionized plane in the polar outflows, Capetti et al. (1995) used the centro-symmetric pattern of the polarization vector to precisely locate the unresolved AGN in the HST/FOC observation of NGC 1068 (see Fig.1, left panel). Kishimoto (1999) removed the plane assumption and studied the polar winds densities and the resulting polarization degree to produce a three dimensional map of the clumps in the outflows. We report results in good agreement with previous studies with improved detection significance, see Fig. 1 for the test case of NGC 1068.

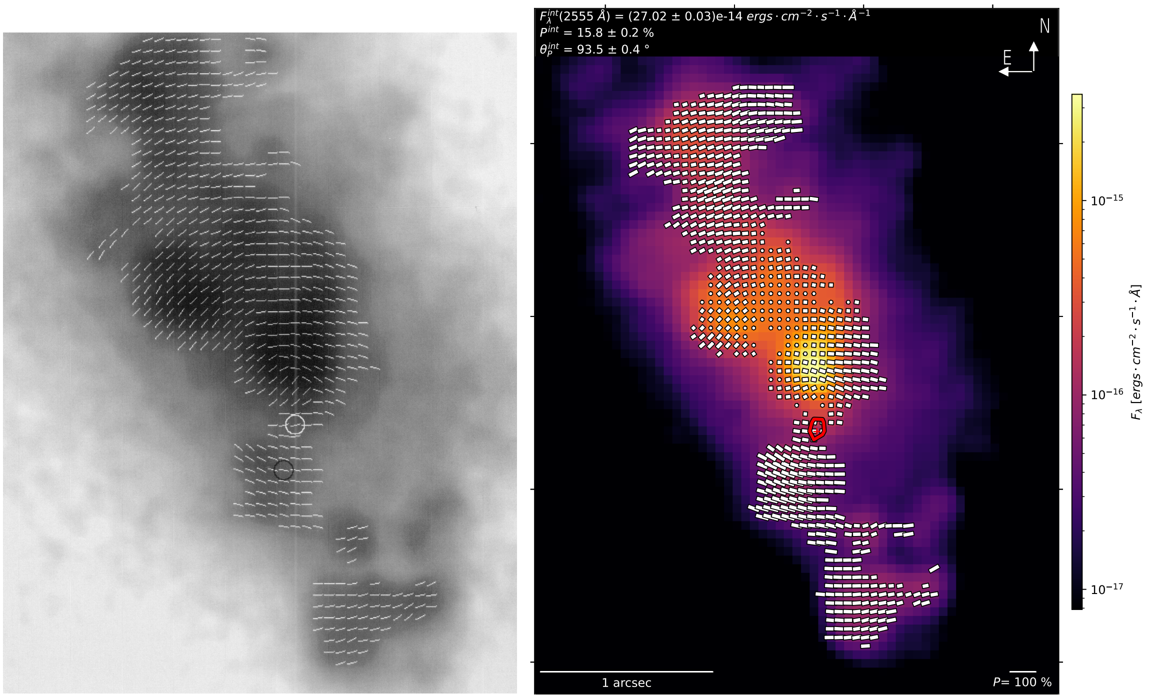

Fig. 1. HST/FOC polarization map of NGC 1068, Proposal ID 5144. **Left:** First reduction to $0.1'' \times 0.1''$ pixels as presented in Capetti et al. (1995), the white circle display their estimation for the nucleus location with 1-σ uncertainty (updated form the black circle). **Right:** Reduction with the new pipeline to $0.043'' \times 0.043''$ pixels as presented in Barnouin et al. (2023), the polarization vectors are shown for a 99% confidence level on the Q and U Stokes flux. The red contour display the 99% confidence level location of the nucleus from the centro-symmetric polarization pattern.

3 Multi-wavelength study of NGC 1068

We present a radio-to-X-rays correlation of the observed intensity and polarization from NGC 1068's polar outflows and nucleus. The radio map is a combined *enhanced*-Multi Element Radio Linked Interferometer Network (*e*-MERLIN) and Very Large Array (VLA) images constructed between 4 and 12 GHz (Mutie et al. 2024). The central region shown in Fig.2 resolves the compact radio components, including the AGN. The full image (cropped here) also displays the extended emissions from the NE and SW jet lobes (see Mutie et al. 2024). Due to the pointing uncertainties between the ground antennas and the HST, the FOC polarization map was aligned with the combined *e*-MERLIN/VLA image on the nucleus location, displayed as a green cross in Fig.2. This fine alignment is made possible by the very high resolution of the radio images in the one hand, and by the strong confidence on the location of the nucleus brought by the centro-symmetric pattern of polarization vectors of the FOC map in the other hand. The latest X-ray polarimetry measurement acquired with the Imaging X-ray Polarimeter Explorer (IXPE) in January 2024 (Marin et al. 2024) probes the torus itself and has been added to the image.

The superposition of the radio intensity map with the near-UV intensity contour shows slight displacement between the hot-spots on both maps, hinting towards interactions between the radio jets and the ionized polar winds. At those locations, the UV polarization decrease in value, a characteristic signature of a perturbed medium. The polarization degree is higher where radio emission is the weakest, basically where UV photons can scatter off unperturbed polar winds. We note that the polarized X-ray emission arise from a region (the core) that is not coincident with the peak of radio nor UV emission. Indeed soft X-ray (and UV) photons have to scatter off the optically-thick torus funnel before escaping, leading to strong polarization ($\geq$ 15%) with a polarization position angle perpendicular to the jet axis. This allowed Marin et al. (2024) to put new independent constraints on the AGN inclination in the range 42°–87° and on the torus half-opening angle in the range 40°–57.5°. These values are in agreement with the ranges determined in other energy bands and help connect the jets and polar winds to the central engine. Further polarimetric studies in the UV and X-ray bands are needed to improve the significance of the results.

4 Conclusions

The FOC instrument onboard HST was the last polarimeter with UV capabilities to ever fly and since its decommission in 2002 its archival data remain state-of-the-art. Thanks to improvements in HST calibration and reduction methods, we revamped the analysis of the AGN sample among the archives, some of which were never published despite their great quality. With the help of multi-wavelength study, we present here a map of NGC 1068 that paint the finest portrait of the AGN obtained to this day. The radio and UV maps highlight the interactions between the jets and its clumps inside of the ionized polar winds. The first X-ray polarimetric measurement puts strong constraints on the dusty torus half-opening angle and its orientation, giving us an even better insight on the direction of the winds and jets. Such deep knowledge of this archetypal type 2 AGN has been rendered possible thanks to the study of its polarized light, which allows us to look past the obscuring torus and towards the innermost parts of the AGN engine. To further complement our understanding of AGNs, new polarimetric missions in the UV band are required, such as POLLUX that could be embarked on the Habitable World Observatory (HWO) mission (Muslimov et al. 2024).

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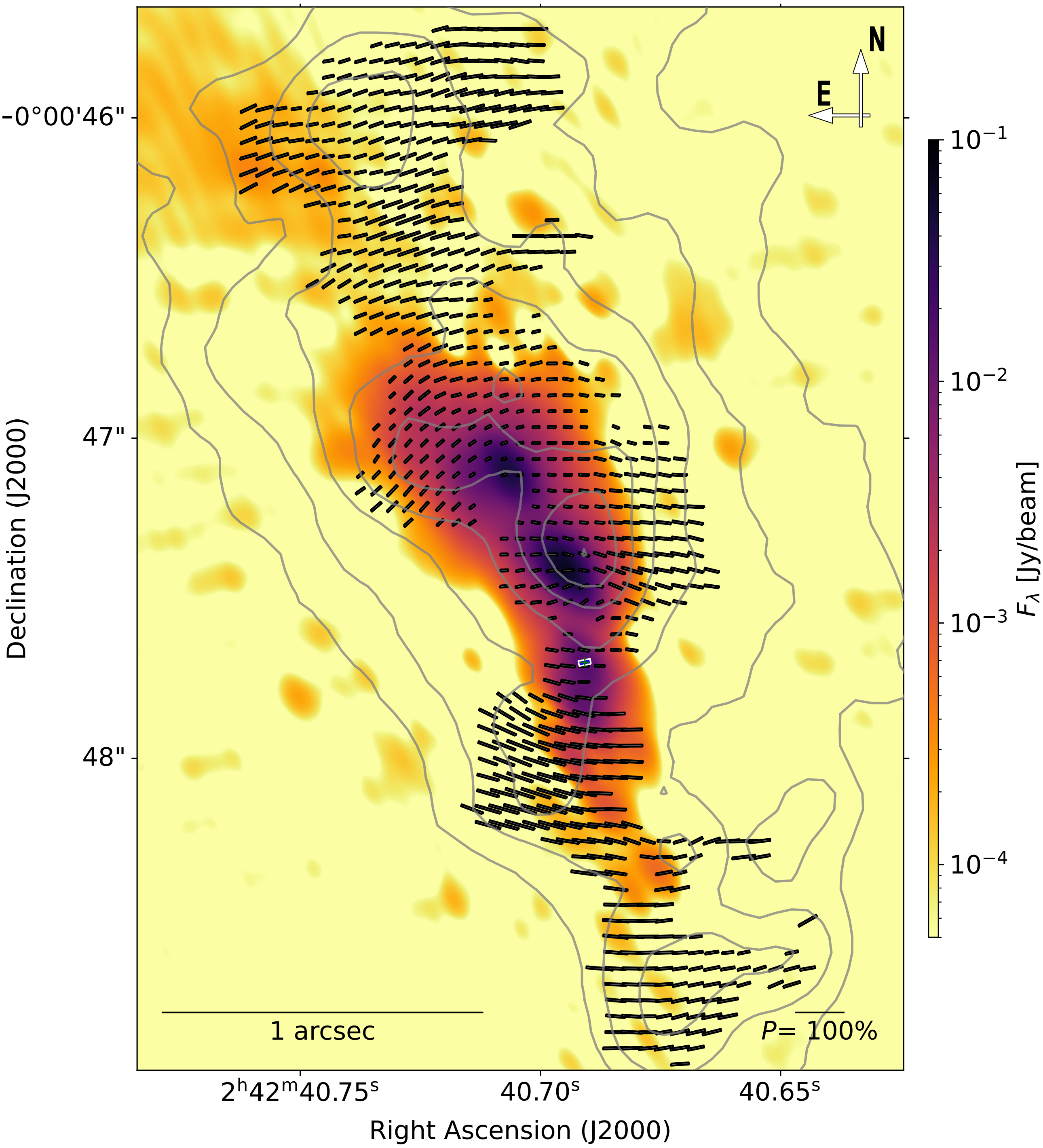

Fig. 2. Multi-wavelength view of NGC 1068. On the 4-12 GHz high-resolution colored map from *e*-MERLIN/VLA (Mutie et al. 2024) are superposed the intensity contour (gray) and polarization map (black vectors) in near-UV from the HST/FOC (Barnouin et al. 2023), as well as the 2–8 keV polarization detection from IXPE (Marin et al. 2024). The observed X-ray polarization is $P = 12.4 \pm 3.6\%$ at $\Psi = 100.7 \pm 8.3°$ and is displayed as a blue vector with white edges and its size doubled for better visibility.