

PROBING THE STRUCTURE AND EVOLUTION OF ACTIVE GALACTIC NUCLEI WITH THE ULTRAVIOLET POLARIMETER POLLUX ABOARD LUVOIR

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Abstract. The ultraviolet (UV) polarization spectrum of nearby active galactic nuclei (AGN) is poorly known. The Wisconsin Ultraviolet Photo-Polarimeter Experiment and a handful of instruments on board the Hubble Space Telescope were able to probe the near- and mid-UV polarization of nearby AGN, but the far-UV band (from 1200 Å down to the Lyman limit at 912 Å) remains completely uncharted. In addition, the linewidth resolution of previous observations was at best 1.89 Å. Such a resolution is not sufficient to probe in detail quantum mechanical effects, synchrotron and cyclotron processes, scattering by electrons and dust grains, and dichroic extinction by asymmetric dust grains. Exploring those physical processes would require a new, high-resolution, broadband polarimeter with full ultraviolet-band coverage. In this context, we discuss the AGN science case for POLLUX, a high-resolution UV spectropolarimeter, proposed for the 15-meter primary mirror option of LUVOIR (a multi-wavelength space observatory concept being developed by the Goddard Space Flight Center and proposed for the 2020 Decadal Survey Concept Study).

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1 Introduction

The far and mid-ultraviolet polarization of nearby active galactic nuclei (AGN) is largely uncharted territory. Only two missions were equipped with ultraviolet (UV) polarimeters in the past.

The first one was WUPPE, the Wisconsin Ultraviolet Photo-Polarimeter Experiment (Nordsieck & Code 1982; Stanford et al. 1985; Code & Nordsieck 1989). The telescope, designed and built at the University of Wisconsin Space Astronomy Laboratory in the 1980's (PI: Arthur D. Code), was a pioneering effort to explore polarization and photometry at UV wavelengths. WUPPE was designed to obtain simultaneous spectra and polarization measurements from 1400 to 3300 Å. It consisted of a 0.5m f/10 classical Cassegrain telescope and a spectropolarimeter, with a field of view of 3.3 by 4.4 arc-minutes and a resolution of 6 Å. Its effective area was about 100 cm² at 2300 Å. WUPPE flew on two NASA Space Shuttle missions: ASTRO-1 and ASTRO-2. It was one of three ultraviolet telescopes (with the Hopkins Ultraviolet Telescope and the Ultraviolet Imaging Telescope) and one X-ray telescope (the Broad Band X-Ray Telescope) on the ASTRO-1 payload which flew on board the Space Shuttle Columbia on December 2 – 11, 1990. The telescope was re-flown on March 2 – 18, 1995 on board the Space Shuttle Endeavour. In total, WUPPE-1 and WUPPE-2 obtained UV spectropolarimetry (and spectra) for 121 objects over 183 observations. These 121 objects include only 2 radio-quiet AGN (NGC 4151, NGC 1068), 2 radio-loud AGN (3C 273, Centaurus A), and 1 BL Lac object (Mrk 421). These

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AGN observations, at the exception of NGC 1068 (shown in Fig. 1), had very poor spectral resolution. Most of the UV polarimetric measurements had to be spectrally rebinned because of the combined effects of source brightness, WUPPE sensitivity limit, and too short integration times.

The second mission with UV polarimetric capabilities was the Hubble Space Telescope (HST). Two instruments on board HST allowed optical, near- and mid-UV polarimetry: the Faint Object Camera (FOC) and the Faint Object Spectrograph (FOS). Both instruments were among the four original axial instruments on board HST and they were designed to take observations from 1150 to 6500 Å. The FOS was removed from HST during the Second Servicing Mission in February 1997, and the FOC during Servicing Mission 3B in March 2002. Later on, UV/blue filters ($\lambda > 2000$ Å) were mounted on the Advanced Camera for Surveys (ACS) and the Wide Field and Planetary Cameras (WFPC) 1 and 2, for polarimetric observations. Altogether,* the polarimetric instruments on board HST observed 117 AGN (108 objects with imaging-polarimetry, 76 objects with spectropolarimetry, and a handful with both; Enrique Lopez-Rodriguez, private communication) from Cycle 0 through Cycle 22. HST UV polarimetry provided strong constraints on the polarization mechanism in AGN (Antonucci et al. 1994), highlighted the three-dimensional structure of the nuclear region of NGC 1068 (Kishimoto 1999), and allowed accurate determination of the position of the source of scattered radiation (Capetti et al. 1995). Heavily obscured AGN (such as Mrk 231) were observed to probe the composition of dust and low-ionization gas clouds (Smith et al. 1995). UV polarization also helped unveil the characteristics of the magnetic-field pattern in the jet of M87 (Boksenberg et al. 1992) and probed the synchrotron origin of optical polarization in the BL Lac object PKS 2155-304 (Allen et al. 1993).

Both WUPPE and HST polarimetric observations brought important results in the field of AGN. They were, however, restricted to low-resolution capabilities (FOS linewidths 1.89 – 1.97 Å, for a 3.7" x 1.3" and 0.26" aperture, respectively) and did not reach wavelengths below 1150 Å. This is unfortunate, because polarization induced by scattering on small dust grains rises steeply into the blue (1200 – 3600 Å, Kartje 1995). Moreover, contamination by the background starlight of AGN-host galaxies is about three orders of magnitude lower at 0.1 μm than at 1 μm (for spiral galaxies, see Bolzonella et al. 2000). Hence, the contrast of polarimetric observations is expected to increase significantly from longer to shorter wavelengths, leaving today a vast new parameter space to be explored by a new high-resolution instrument.

2 The LUVOIR mission and the POLLUX instrument

The Large Ultraviolet/Optical/Infrared Surveyor (LUVOIR) is one of four “flagship” mission concept studies led by NASA for the 2020 Decadal Survey. LUVOIR is a concept for an ambitious, multi-wavelengths 15-m observatory that would enable a great leap forward in a broad range of astrophysical topics, from the epoch of re-ionization, through galaxy formation and evolution, to star and planet formation. LUVOIR also has the major goal of characterizing a wide range of exoplanets, including those that might be habitable - or even inhabited. If LUVOIR is selected during the Decadal evaluation, this mission would be launched in 2035.

The study of LUVOIR will extend over three years and be executed by the Goddard Space Flight Center, under the leadership of a Science and Technology Definition Team (STDT). Under the impulsion of the Laboratoire d’Astrophysique de Marseille (LAM) and the Laboratoire d’études spatiales et d’instrumentation en astrophysique (LESIA), European institutes have come together to propose an instrument that would be on-board the 15-meter primary mirror option of LUVOIR. This instrument, POLLUX, is a high-resolution spectropolarimeter operating at UV wavelengths (900 – 4000 Å). LUVOIR will be equipped with 4 instruments: 1) a coronagraph called ECLIPS, 2) HDI, a near-UV to near-IR imager, 3) a multi-object low and medium resolution UV spectrograph and imager called LUMOS, and 4) POLLUX. The first 3 instruments are being studied by NASA, while POLLUX is being studied by a European consortium led by France.

In its actual design, POLLUX would resolve narrow UV emission and absorption lines, following the various forms of AGN feedback into the interstellar and intergalactic medium. The most innovative characteristic of POLLUX is its unique spectropolarimetric capability that will enable detection of the UV circular and linear polarization from almost all types of sources, providing a full picture of their scattering and magnetic field properties. Since the parameter space opened by POLLUX is essentially uncharted territory, its potential for ground-breaking discoveries is tremendous. It will also neatly complement and enrich some of the cases advanced for LUMOS, the multi-object spectrograph of LUVOIR.

*Accounting for the Near Infrared Camera and Multi-Object Spectrometer (NICMOS), which provides broad-band imaging polarimetry in the wavelength range 0.8 – 2.5 μm

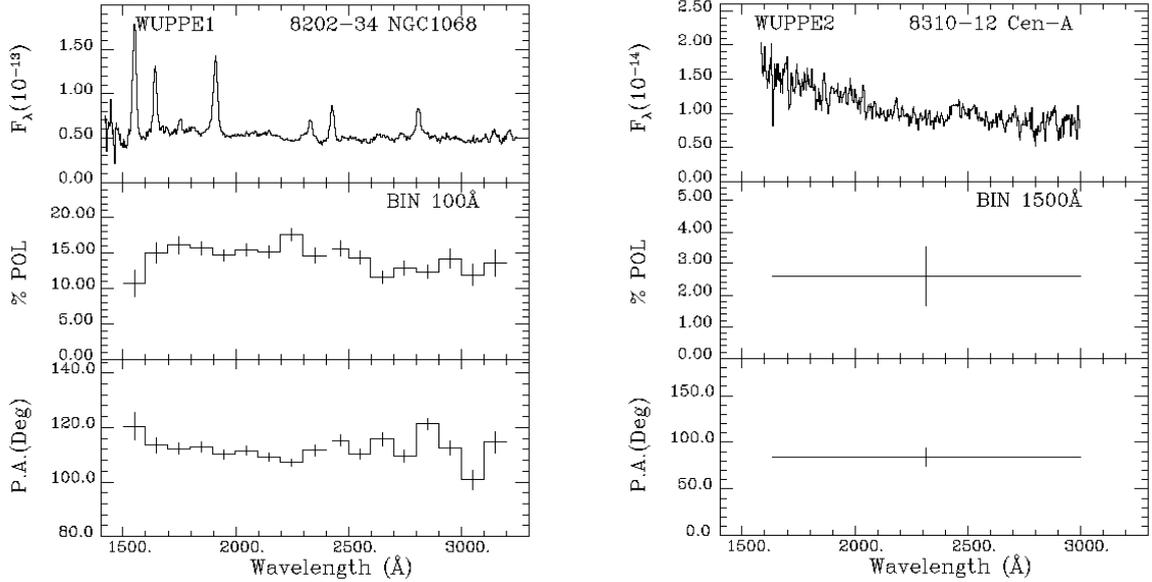


Fig. 1: WUPPE UV spectropolarimetry of the radio-quiet AGN NGC 1068 (left) and the radio-loud AGN Centaurus A (right). Both are type-2 AGN (the view of the central engine is blocked by an optically thick, equatorial, dusty medium) and they have comparable GALEX fluxes (about 28 mJy at 1524 Å). In the case of NGC 1068, the exposure time was 1972 seconds. Observation of Centaurus A was 1152 seconds long. Data from the Barbara A. Mikulski Archive for Space Telescopes (MAST) and from Code et al. (1993).

3 AGN science with POLLUX

POLLUX will offer unique insights into the still poorly-known physics of AGN, in particular by probing UV-emitting and absorbing material arising from accretion disks, synchrotron emission in jet-dominated AGN and large-scale outflows. Some key signatures of accretion disks can be revealed only in polarized light, and with higher contrast at ultraviolet than at longer wavelengths. Specifically, models of disk atmospheres usually assume Compton scattering in an electron-filled plasma, resulting in inclination-dependent polarization signatures (up to 10%, see e.g., Chandrasekhar 1960). Yet optical polarization is detected at less than a percent, and parallel to the radio jets if any (Stockman et al. 1979). Whether these low levels can be attributed to dominant absorption opacity (Laor & Netzer 1989) or complete Faraday depolarization (Agol & Blaes 1996) is unclear. This degeneracy can be broken by looking at the numerous UV spectral lines that are formed in the innermost AGN regions (e.g, Ly α λ 1216, C II λ 1335, C IV λ 1549, Mg II λ 2800 ...). These lines are the key to understanding UV polarization, and only observations with high signal-to-noise ratio and high spectral resolution can distinguish between the two effects. If absorption opacity is responsible for the low continuum polarization we detect, the line profiles should also show a significant drop in polarization.

Another interesting feature coupled with the accretion disk is the strong polar magnetic field that ultimately launches jets. Dissipative processes in the accretion disk transfer matter inward, angular momentum outward, and heat up the disk. Magnetic-field lines from the inner part of the accretion disk cross the event horizon of the black hole and are wound up by its spin, launching Poynting flux-dominated outflows. The resulting jets tend to be collimated for a few parsecs and to dilute in giant lobes on kilo-parsec scales. Relativistic electrons traveling in ordered magnetic fields are responsible for the high polarization we detect (of the order of 40 – 60%, see e.g., Thomson et al. 1995). Interestingly, the continuum-polarization degree and angle are extremely sensitive to the strength and direction of the magnetic field, and to the charge distribution. This will allow POLLUX to probe in great detail the magnetic configuration of such jets by measuring the electron-beam polarization. If a jet is inclined toward the observer (blazar-like objects), a non-thermal spectral energy distribution will be observed, with a low-energy broadband peak in the radio-to-UV wavelength range. Comparing the observed UV polarization of blazars to leptonic, hadronic or alternative jet models (e.g., Zhang 2017) will enable better constraints on the composition and lifetimes of particles in the plasma. Since jets are also responsible for ion

and neutrino emission, they are valuable sources to understand how cosmic rays are produced.

In addition to jets, strong polar outflows will be important targets for POLLUX. At redshift greater than 1.5 – 2, a sub-category of quasars, called Broad-Absorption-Line quasars (BAL QSO), exhibit very broad absorption features in UV resonant lines ($\text{Ly}\alpha$, C IV, Si IV). The gas outflows producing these signatures presumably contribute to the enrichment of the quasar host galaxies (a process generally referred to as ‘feedback’). BAL QSO are particularly interesting as they tend to have high polarization degrees (e.g., Ogle et al. 1999), which can be used to constrain wind geometry (Young et al. 2007). These BAL QSO are believed to be the high-redshift analogs of more nearby, polar-scattered Seyfert galaxies, whose UV emission will also be explorable with POLLUX. In particular, POLLUX will help investigate the dependence of broad absorption lines on bolometric luminosity and thus the role of radiative acceleration in the appearance of these lines (Arav & Li 1994; Arav et al. 1994). High-resolution spectropolarimetry will also enable new constraints on wind kinematics, for the first time from UV resonance lines, similarly to what has been achieved by Young et al. (2007) using the $\text{H}\alpha$ line.

Combined with the UV, optical and IR capabilities of the other instruments on board LUVOIR, POLLUX will allow unprecedented insight into the composition of AGN dust. In the Galaxy, the dust extinction, which is highest in the UV, shows a local peak near 2175 Å (Stecher & Donn 1965). The strength of this feature varies from galaxy to galaxy: it is weaker in the Large and Small Magellanic Clouds than in the Galaxy and almost never observed in AGN (Gaskell & Benker 2007). Unveiling the mineralogy of extragalactic dust grains is not easy and requires high-quality extinction-curve measurements. A strong advantage for POLLUX is that the polarization induced by dust scattering rises rapidly toward the blue, peaking near 3000 Å in the rest frame and remaining nearly constant at shorter wavelengths (see, e.g., Hines et al. 2001). Polarimetry at short wavelengths can thus discriminate between dust scattering and wavelength-independent electron scattering. Additionally, polarization measurements with POLLUX can be enhanced by dust-grain alignment: theory predicts that paramagnetic grains will be aligned with their longer axes perpendicular to the local magnetic field if exposed to magnetic or anisotropic-radiation fields with wavelengths less than the grain diameter (Lazarian & Hoang 2007). Therefore, the UV band will selectively trace the smallest dust grains and allow better characterization of AGN dust composition. For such grains, the polarization strength is predicted to be proportional to the magnetic-field strength, enabling POLLUX to also measure for the first time the intensity and direction of the magnetic field on parsec scales around the AGN core (Hoang et al. 2014). Finally, the radiative pumping of atoms and ions with fine structure is predicted to align these with the magnetic field, giving rise to polarized-line emission. A number of prominent UV lines are predicted to show significant polarization following that mechanism, providing a mean of tracing the magnetic field in hot AGN gas on small scales (Yan & Lazarian 2008).

4 Conclusions

We have highlighted the need for a high-resolution spectropolarimeter covering the full ultraviolet band to study a wealthy range of astrophysical sources, emphasizing on the still poorly-constrained AGN physics. Concretely, POLLUX will probe the location, geometry and composition of the regions responsible for UV emission and enable measurements of their magnetic-field strength and topology. Measurements of UV polarization due to dust scattering by magnetically aligned grains will allow one to assess the strength and direction of the magnetic fields that are shaping the AGN outskirts. Outflows, jets and feedback, which drive the co-evolution of the AGN and their host galaxies, will be probed at unprecedented resolution.

The AGN science case of POLLUX would fully benefit from the broad wavelength coverage of LUVOIR to investigate the properties of accretion disks and jets. By the time LUVOIR would be launched (≥ 2035), it would fully take advantage of X-ray coverage by ATHENA observations to probe the physics of accretion (Nandra et al. 2013). From the ground, sub-millimeter, millimeter and radio observations from large arrays of antennae such as SKA (Acero et al. 2017) will probe the low-energy end of AGN spectra, together with high-resolution images of the central parsecs and jets. Interferometry, in particular in the infrared domain, will enable subparsec-resolution images of the hot and cold dust components.

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