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Insights into the changing-state AGN phenomenon from the variability of Mrk 1018

S. Veronese[a,b,*] **and C. Vignali**[c,d]

[a] *Netherlands Institute for Radio Astronomy (ASTRON),*
Postbus 2, 7990 AA Dwingeloo, The Netherlands
[b] *Kapteyn Astronomical Institute, University of Groningen,*
PO Box 800, 9700 AV Groningen, The Netherlands
[c] *Dipartimento di Fisica e Astronomia Augusto Righi, Università degli Studi di Bologna,*
Via Gobetti 93/2, 40129 Bologna, Italy
[d] *INAF – Osservatorio di Astrofisica e Scienza dello Spazio di Bologna,*
Via Gobetti 93/3, 40129 Bologna, Italy

E-mail: veronese@astron.nl

Changing-state active galactic nuclei (CS-AGN) do not align with our current understanding of AGN physics. In this short paper, we report recent work on Mrk 1018, a CS-AGN candidate at $z = 0.043$ exhibiting dramatic, broadband spectro-photometric variability on a timescale of ~ 10 years, which provides new insights into the CS-AGN phenomenon. A comprehensive analysis of the X-ray spectra, optical-to-X-ray spectral energy distribution, and photometry suggests that Mrk 1018 is indeed a CS-AGN. Indeed, evidence for the activation or strengthening of a relativistic jet during the state transition, similarly to what happens in star-black hole X-ray binaries, is compelling. It is further speculated that the transition is caused by the close passage of a gaseous cloud near the accretion disk, linking sub-parsec accretion physics to the large-scale phenomena occurring in the host galaxy.

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[*] Speaker

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1. Introduction

Active Galactic Nuclei (AGN) are powerful ($L \gtrsim 10^{42}$ erg s^{-1}) astronomical sources resulting from the accretion of matter onto the supermassive black hole (SMBH) typically hosted at the centre of galaxies (see the reviews [1–4]). The large amount of energy released arises mainly from viscous dissipation: the gas orbiting the SMBH at sub-parsec distances loses angular momentum, heats up, and radiates. At high densities ($N \sim 10^{24}$ cm^{-3}), the accretion flow is optically thick and geometrically thin; thus, its cooling is thermal, resembling black-body radiation that peaks in the UV for typical SMBH masses of $\mathrm{M_{SMBH}} \sim 10^6$ M$\odot$ and above [5–7]. This accretion is known as the 'radiative mode'. At lower densities, the flow is optically thin and geometrically thick. In this 'advective mode' of accretion, the cooling is non-thermal, and relativistic jets of charged particles, emitting synchrotron radiation, are likely launched from the inner boundary of the disk [8–10]. The photons released by the accretion disk propagate through a Comptonising medium, usually referred to as the 'corona', whose geometry and physical properties are still debated [11–16]. However, this sub-parsec region is essential for explaining the high-energy ($E > 0.1$ keV) emission from AGN: a fraction of the photons released by the accretion disk are upscattered to X-ray energies via synchrotron self-Compton and inverse Compton processes within the corona. The ionising UV radiation that escapes the corona is transmitted through the broad-line region (BLR), a sub-parsec scale structure of gaseous clouds still gravitationally bound to the SMBH [17–20]. Here, the UV photons ionise the gas, which emits broad ($v > 10^3$ km s^{-1}) optical lines. As the UV front propagates through the interstellar medium (ISM) of the galaxy, it ionises the gas at kpc distances from the SMBH, producing narrow optical lines [21, 22]. AGN exhibiting both the broad and narrow components are classified as 'type 1', whereas 'type 2' AGN lack the broad lines in their optical spectrum.

According to the AGN unification model [23], the type 1-type 2 distinction arises from the orientation of the dusty torus surrounding the SMBH at parsec scales [24, 25]: in type 2 AGN, the torus obscures the BLR, while in type 1 AGN, the BLR is directly visible. However, this classification cannot be solely attributed to orientation, as some AGN exhibit dramatic variability in their optical emission lines, with the broad component appearing or disappearing over timescales of days to decades [26–30]. These 'changing-look AGN' (CL-AGN) remain a challenge in AGN physics, with proposed explanations including variations in column density [31–33], eclipsing events, disk instabilities [33, 34], accretion-rate fluctuations [35, 36]. In a recent review article, Ricci et al. [37] distinguish CL-AGN into changing obscuration (CO-AGN) and changing state (CS-AGN) AGN. In the former class, the variability is triggered by differences in the line-of-sight column density, mostly associated with clouds temporarily eclipsing the BLR. In CS-AGN, it is the accretion rate that varies, probably leading to a switch in the accretion mode. The discovery of this exceptional class of AGN immediately raises several questions, the most important of which were already listed by Ricci et al.: how common are CS-AGN, and what is their typical variability timescale? Is the state transition related to certain physical aspects of the AGN? What drives the state transition?

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Table 1: Mrk 1018 main observational properties.

Parameter	Mrk 1018	References
R.A. (J2000) [hh mm ss]	02 06 16.0	[38]
DEC. (J2000) [deg arcmin arcsec]	-00 17 29.2	[38]
Redshift	0.043	[39]
Luminosity distance [Mpc]	190.2	
Scale length [kpc/arcsec]	0.848	
Morphology	S0	
Stellar Mass [$M_\odot$]	8.3×10^{10}	[40]
M_{BH} [$M_\odot$]	7×10^{7}	[41]

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2. Mrk 1018

One of the most promising CS-AGN candidates is Mrk 1018 (see Table 1 for its main observational properties). Initially otically classified as a type 2 AGN in 1981 [42], subsequent observations revealed the emergence of broad emission lines and a steep increase in Hβ flux, prompting its re-classification as type 1 [43, 44]. Early interpretations linked this variability to UV continuum brightening [43] or the dissipation of obscuring material [44]. No further studies were conducted on this source until 2016, when the Close AGN Reference Survey [27, 45] compared Sloan Digital Sky Survey (SDSS) spectra from 2003 with Multi-Unit Spectroscopic Explorer (MUSE) spectra from 2015. This revealed the disappearance of the broad lines, accompanied by a dimming of the source optical continuum.

Several hypotheses were initially proposed to explain Mrk 1018 behaviour, including tidal disruption events [27], obscuring cloud transits [27, 45, 46], fuel depletion [27], binary SMBHs [27, 45], and recoiling SMBHs [47]. Recently, the debate on Mrk 1018 shifted towards the possibility of this AGN being a CS-AGN [48–51]. However, despite these efforts, limitations in spectral coverage, statistics, and temporal sampling have prevented conclusive interpretations.

Veronese et al. [52] overcame these limitations, analysing all available X-ray, optical, and UV data from Chandra [53], XMM-Newton [54], Swift [55], and NuSTAR [56] to investigate the mechanisms driving Mrk 1018 variability. Their dataset spans the 2005 to 2019 period, covering the epoch when the AGN was in the bright state (2005 to 2012) and the faint state (2012 to 2019). From the photometric analysis, they confirmed the broadband dimming of the source, with the optical, UV, and X-ray continuum luminosities decreasing by factors of > 7, > 24, and > 9, respectively (see Figure 1). They proposed that this variability is prompted by an initial decline in the UV emission from the accretion disk. The X-ray spectra fit a model where the emission originates from a hot ($kT \sim 100$ keV), optically thin spherical corona surrounding the SMBH, and a warm ($kT < 1$ keV) Comptonising medium in the inner accretion flow. Multi-epoch spectroscopy revealed that the X-ray emission became harder during the faint state. Indeed, the hardness ratio

$$H_R = \frac{F_{2-10\,\mathrm{keV}} - F_{0.5-2\,\mathrm{keV}}}{F_{2-10\,\mathrm{keV}} + F_{0.5-2\,\mathrm{keV}}} \tag{1}$$

evolved from 0.2 ± 0.1 to 0.4 ± 0.1. This spectral hardening reflects the state of the two coronae. On the one hand, the physical properties of the hot corona did not change between the bright and faint

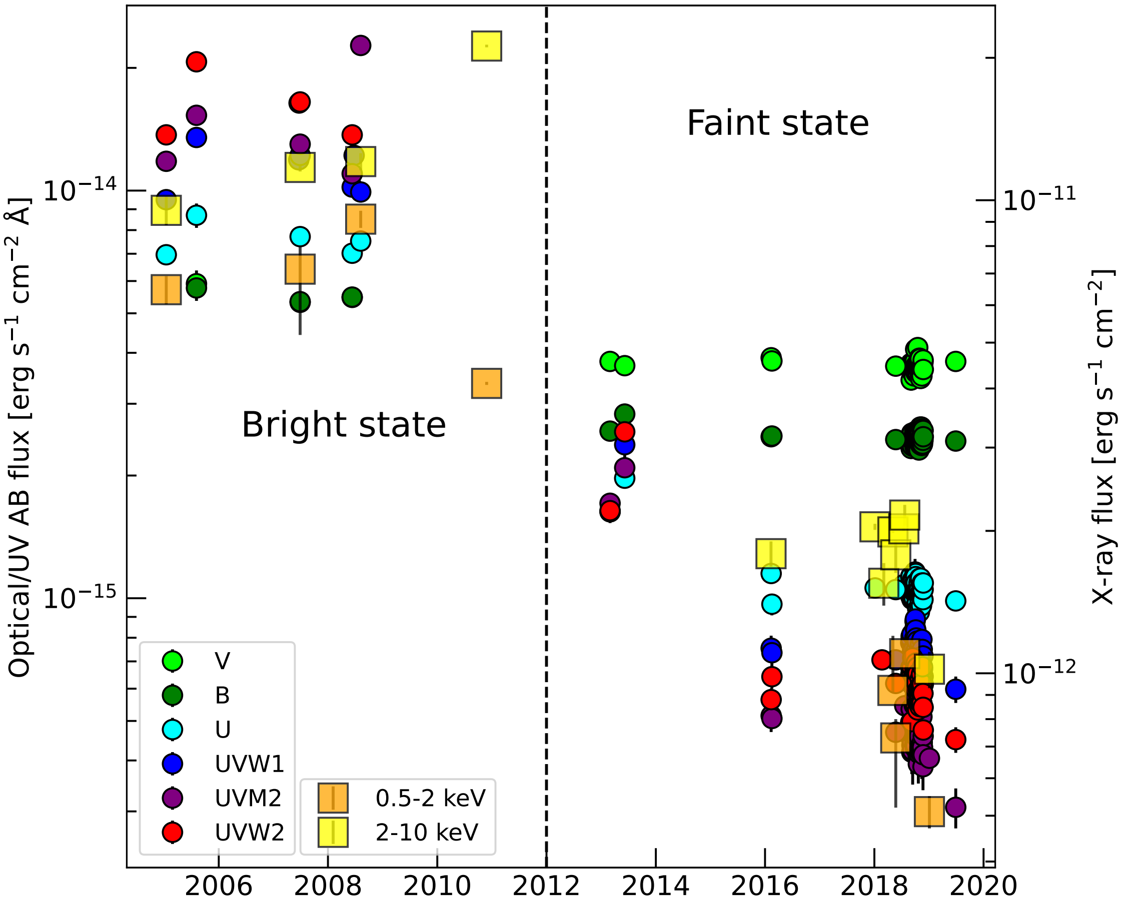

Figure 1: Mrk 1018 optical, UV, and X-ray photometry from Veronese et al. [52]. The coloured circles represent the optical and UV filters: V in green, B in dark green, U in cyan, $UVW1$ in blue, $UVM2$ in purple, and $UVW2$ in red. Orange and yellow squares indicate the 0.5–2 keV and 2–10 keV X-ray fluxes. The left-hand y-axis corresponds to the optical and UV fluxes, while the right-hand y-axis corresponds to the X-ray photometry. The vertical black dashed line distinguishes between the bright and faint states.

states; on the other hand, the warm corona cooled (kT from 0.4 to 0.2 keV) and its emission almost disappeared (1 keV flux from $\sim 1.3 \times 10^{-3}$ to $\sim 0.05 \times 10^{-3}$ photons cm^2 keV^{-1} s^{-1}). Veronese et al. argued that the declining UV emission and the cooling of the warm corona are the result of variations in the magnetic fields, which are in turn caused by the state change of the inner accretion flow from radiative to advective.

3. The proposed changing-state scenario

The idea that the variability of Mrk 1018 could be due to a change of state in the accretion flow was first proposed by Noda et al. (2018) [48]. Veronese et al. add further evidence in support of this scenario. First, the harder X-ray emission during the faint state mirrors the behaviour of stellar-mass black hole X-ray binaries transitioning from active to quiescent phases [58–60]. In these systems, the accretion evolves from the radiative to the advective mode, which extracts magnetic energy

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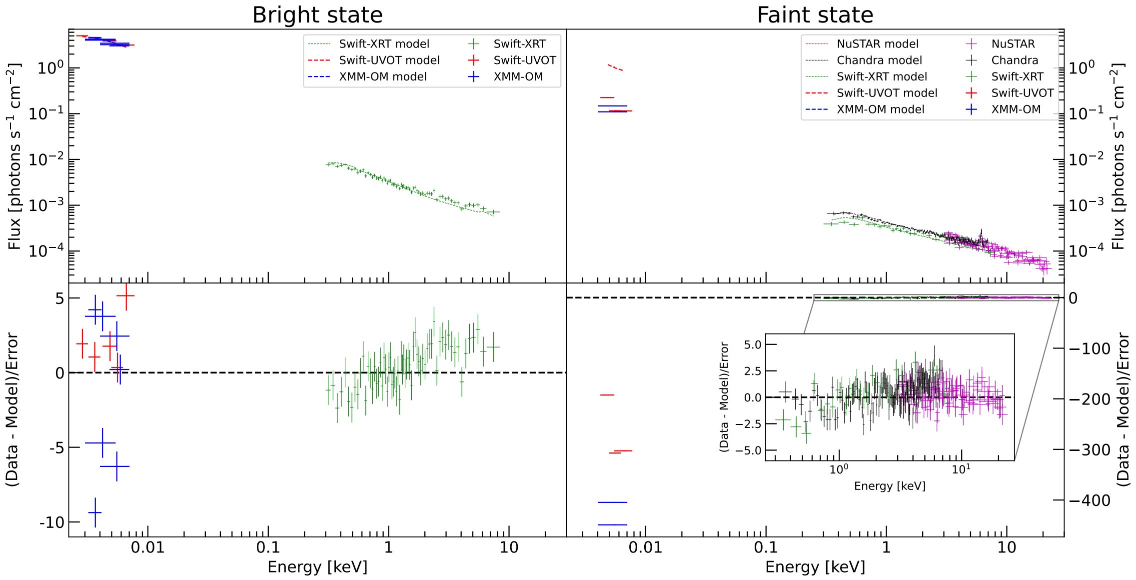

Figure 2: Mrk 1018 optical-to-X-ray SED from Veronese et al. [52]. The top panels show the SED for the bright (left) and faint state (right), whereas the bottom panels display the residuals, expressed in terms of $(data - model)/error$, for the radiative disk model of Kubota & Done [57]. The bottom-right inset panel contains a zoom-in of the X-ray residuals. The horizontal black dashed line indicates the zero level. XMM-OM and Swift-UVOT data are shown in blue and red, respectively. Chandra and NuSTAR spectral points are indicated in black and purple, respectively. XMM-Newton data are not shown to avoid overcrowding. The best-fit model for each telescope is represented by bold lines in corresponding colours.

and weakens the magnetic fields. Since soft X-ray emission originates in the inner accretion flow and is the most variable X-ray component for Mrk 1018, Veronese et al. proposed that the state transition occurs in the inner accretion flow. Second, performing a spectral energy distribution (SED, see Figure 2) fitting using the optical, UV, and X-ray fluxes and the radiative disk model from Kubota & Done (2018) [57], Veronese et al. found that, in the bright state, the SED of Mrk 1018 is well reproduced by a radiative accretion disk. In contrast, in the faint state, the UV emission is severely overestimated by the model. This is consistent with the expectation of the inner accretion flow turning advective. Third, Veronese et al. derived the Eddington-normalized accretion rate ($\mu = \frac{\dot{M}}{\dot{M}_{EDD}}$) from the SED and the model-independent 3000Å bolometric luminosity (L_{3000}; [61]). Indeed, Kubota & Done [57] found a critical value ($\mu_c = 0.02$) that distinguish radiative ($\mu > \mu_c$) and advective ($\mu < \mu_c$) accretion disks. Comparing with μ_c the derived μ values for Mrk 1018, Veronese et al. found that during the bright state $\mu > \mu_c$ for both the SED and L_{3000} derivation. Instead, during the faint state $\mu < \mu_c$ for both methods. This result again supports the proposed changing-state scenario. Finally, another compelling evidence for the changing-state scenario are recent, multi-epoch pc-resolution VLBI observations of the galactic center [62]. If Mrk 1018 is undergoing inefficient accretion, much of the energy should manifest as a jet. Walsh et al. found a shift in the position of the radio core and a variation in spectral index between 2014 and 2021. Their interpretation is that these findings could hint the empowering or formation of a jet, in agreement with the expectation from the changing-state scenario.

This scenario explains both the spectral and photometric variability of Mrk 1018. The transition

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from the radiative to the advective mode of accretion shifts the primary energy release mechanism to the jet. The resulting jet reduces magnetic field intensity, leading to four consequences:

- the warm corona cools [63], diminishing soft X-ray emission and causing X-ray hardening;
- the accretion rate drops [51, 64], leading to broadband photometric variability;
- the BLR clouds are pushed outwards, as suggested by signatures of outflows in the optical spectra [45, 51, 65];
- the viscous timescale, which sets the variability timescale, is reduced from the typical 10^{4-7} years [66] to about ~ 10 years [51].

The final piece of the puzzle is what triggered the state transition of the inner accretion flow. Veronese et al. proposed that material funnelled from the host galaxy to the SMBH may have perturbed the accretion flow sufficiently to induce the transition. The infall could result from a recent merging event [67–71], dynamical friction [72–76], or the so-called cold chaotic accretion (CCA) [77–80], a scenario where multi-phase clouds condense in the galactic halo, collide, and sink towards the SMBH. Dynamical friction can also drive massive objects like gas clouds and star clusters inwards [72–76]. Whatever the source of the state transition, Veronese et al. argued that an intrinsic, almost-critical accretion rate is the key factor in establishing the transition, which might explain why CL-AGN are so rare.

4. Conclusions and future prospects

The observed short-term variability of AGN remains poorly understood. Recent detailed studies on Mrk 1018 are providing new insights into this phenomenon. It is suggested that the CS-AGN phenomenon may be driven by large-scale processes (e.g., mergers, CCA) coupled with sub-parsec scale accretion physics (e.g., magnetic fields). Therefore, to improve our understanding, it is imperative to conduct future multi-scale studies focusing simultaneously on AGN and their host galaxies. Several steps remain to validate the changing-state scenario proposed by Veronese et al. for Mrk 1018, and possibly applicable to other CS-AGN. Higher-resolution VLBI observations (< 1 mas) are needed to confirm the presence of the jet and its role in the disappearance of the broad lines. Additionally, pc-resolution observations of the multi-phase gas distribution in the host galaxy and numerical simulations of cloud-disk interactions are essential to distinguish the roles of mergers, dynamical friction, and CCA in triggering state transitions. Furthermore, the almost-critical accretion rate ($\mu \sim \mu_c$) warrants further exploration. If this threshold drives CS-AGN behaviour, a large-scale statistical study of CS-AGN accretion rates is needed to confirm its significance. Efforts has started in this regard, with an increasing number of works being conducted on this topic [81–85]. Finally, developing a robust model for AGN with characteristics like Mrk 1018 is a priority. A promising candidate is the jet-emitting disk-standard accretion disk (JED-SAD) model [59, 86], originally developed for X-ray binaries. If validated, this framework—where large-scale processes trigger accretion disk transitions—could integrate CS-AGN into broader AGN feeding and feedback models [87–89], offering a more comprehensive understanding of these rare but fascinating objects.

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DISCUSSION

ŞÖLEN BALMAN: Where does the optical peak of the changing-look AGN fall in the change from radiative disk into JED-SAD with the interaction of a cloud?

SIMONE VERONESE: The optical radiation comes from the blackbody emission of the disk. For a radiative accretion, the entire disk contributes to the blackbody. In the JED-SAD accretion, the outer disk (i.e., the SAD component) provides the optical continuum.

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