Changing-look active galactic nuclei

Active galactic nuclei (AGNs) are known to show flux variability over all observable timescales and across the entire electromagnetic spectrum. Over the past decade, a growing number of sources have been observed to show dramatic flux and spectral changes, in both the X-ray and the optical/ultraviolet regimes. Such events, commonly described as 'changing-look AGNs', can be divided into two well-defined classes. Changing-obscuration AGNs show strong variability of the line-of-sight column density, mostly associated with clouds or outflows eclipsing the central engine of the AGN. Changing-state AGNs are instead objects in which the continuum emission and broad emission lines appear or disappear, and are typically triggered by strong changes in the accretion rate of the supermassive black hole. Here we review our current understanding of these two classes of changing-look AGNs, and discuss open questions and future prospects.

Supermassive black holes (SMBHs) are ubiquitously found at the centres of most massive galaxies, and grow predominantly through the accretion of material from their surroundings. The accretion process may produce highly luminous radiation across the entire electromagnetic spectrum. Such active galactic nuclei (AGNs) are commonly classified based on their observed optical/ultraviolet (UV) or X-ray spectral properties. In the optical/UV, objects showing both broad (≥1,000 km s⁻¹) and narrow (≤1,000 km s⁻¹) emission lines are classified as 'type 1' AGNs, while those showing only narrow lines are referred to as 'type 2' sources. Several studies use a finer classification scheme, based on increasingly fainter broad emission lines (that is, types 1.2, 1.5, 1.8 and 1.9). In the X-ray, objects showing line-of-sight column densities (N_H) ≥ 10²² cm⁻² are commonly referred to as 'obscured', while those with N_H < 10²² cm⁻² are 'unobscured'. A very good match has been found between these two classification schemes, with the vast majority of type 1 (type 2) AGNs being unobscured (obscured). A good, first-order explanation for these basic, observationally motivated AGN subclasses is provided by the AGN unification model, according to which in type 1 (unobscured) AGNs the central engine is observed at low inclination angles (that is, closer to face-on than edge-on), so that one can see both the broad- and the narrow-line regions. In contrast, type 2 (obscured) AGNs are observed at higher inclinations (that is, edge-on), through large columns of circumnuclear dusty gas, distributed in an anisotropic, axisymmetric structure, probably aligned with the central accretion disk. This so-called dusty torus would obscure the X-ray and optical/UV continuum emission emerging from the central engine, as well as the broad emission lines emerging from the broad-line regions (BLRs; see Fig. 1 in ref. 6). The typical scales of the different components of accreting SMBHs are described in detail in Supplementary Section 1. Over the past decade, it has become clear that additional ingredients should be included in the unification model. In particular, the covering factor of the obscuring material, which could have an important role in the probability of an AGN to be observed as type 1 or type 2 (ref. 8), shows important trends with AGN accretion-driven radiative output, traced through its luminosity and/or Eddington ratio (λ_Edd).

Another element that could affect the spectral properties of AGNs, and their classification into obscured/type 2 or unobscured/type 1, is variability. AGN variability has been observed across the entire electromagnetic spectrum, and on timescales ranging from hours to years. While usually this variability is stochastic and does not exceed tens of per cent, over the past 20 years an increasing number of accreting SMBHs have been observed as they undergo much more dramatic and coherent changes in their spectral properties, over a range of (exceedingly short) timescales. These changes defy the expectations from our basic understanding of AGN structure, and specifically the classical unification model. These events, commonly called changing-look AGNs to denote their varying appearance, have been discovered in both the X-ray and the optical/UV regimes, and are caused by very different physical processes. In the X-ray band, these transformations can be mostly ascribed to changes in the line-of-sight column density (N_H), which are typically produced by gas located near the SMBH (changing-obscuration AGNs, CO-AGNs). In contrast, in the...
optical/UV, these events are usually associated with rapid changes in the accretion-driven radiation field itself, which in turn lead to the suppression, enhancement or indeed (dis-)appearance of the blue continuum and broad optical/UV lines typical of type 1 AGNs (changing-state AGNs, CS-AGNs). Figure 1 illustrates the basic spectral states of AGNs, and thus the potential transitions between them, as viewed in the X-ray and the optical regimes. With the advent of new facilities and surveys focused on the transient universe, including the Vera Rubin Observatory46, the Einstein Probe25, ULTRASAT26 and many others, a full understanding of these peculiar sources will be one of the main novel efforts within the study of AGNs. In this Review, we summarize our current understanding of changing-look AGNs, discussing first CO-AGNs and then CS-AGNs. We stress that throughout this Review, we use the term CL-AGNs to refer to all AGNs that show drastic spectral transitions, regardless of the physical mechanisms driving these changes, and refer to CO-AGNs and CS-AGNs only whenever robust evidence for the corresponding physical mechanism is in hand.

### Changing-obscuration AGNs

Obscuration by neutral intervening gas can leave a clear imprint on the X-ray emission observed in AGNs: as \( N_H \) increases, the photoelectric cut-off is shifted towards higher energies. At \( N_H \lesssim 10^{22} \) cm\(^{-2} \), the effect of Compton scattering becomes important, and the primary X-ray continuum becomes increasingly suppressed and more difficult to detect. Most of the AGNs in the nearby Universe are obscured (that is, \( N_H \lesssim 10^{23} \) cm\(^{-2} \)) to \( (\text{from}) \), and \( \sim 20\%\) of all AGNs are Compton-thick (that is, with \( N_H \gtrsim 10^{24} \) cm\(^{-2} \)). As the column density increases, reprocessed X-ray radiation produced by the circumnuclear material (that is, a Fe Kα line and a Compton hump at \( \sim 20\text{–}30\text{ keV} \)) emerges above the suppressed primary X-ray continuum. Some of the most obscured Compton-thick AGNs, with \( N_H \gtrsim 10^{24} \) cm\(^{-2} \), can show a reflection-dominated spectrum, in which most of the emission can be attributed to reprocessed X-ray radiation (Fig. 2a). Thus, the broad-range X-ray spectra of AGNs offer clear and robust measures of line-of-sight obscuration.

Some AGNs have been found to show temporal variations in the line-of-sight column density50. These CO-AGN can, in the most extreme cases, transition from (to) being obscured by Compton-thin \( (N_H \lessapprox 10^{24} \) cm\(^{-2} \)) material to (from) Compton-thick \( \Delta \log(N_H \) cm\(^{-2} \)) = 1–2 dex). Such transitions are typically observed in the X-ray: given its small size (Supplementary Section 1), the X-ray corona is considerably easier to observe than, for example, the much more extended BLR. Variability in \( N_H \) has provided clear indication that the material around the SMBH is clumpy, and offers unique insights into its dynamics.

### Early works

One of the first known cases of clear column-density variability was discovered in the nearby broad-line AGN NGC 4151. X-ray observations of this source carried out in December 197651 found a \( N_H \) that is about four-times higher than that determined from data taken in January of the same year52. A similar variation was detected in the AGN ESO 103–G35, which was found to show a change in \( N_H \) of a factor about 2 over a period of 90 days51. The discovery of yet more extreme \( N_H \) variations came a few years later, from observations of NGC 1365. This AGN was observed by the Advanced Satellite for Cosmology and Astrophysics (ASCA) in 1994 and found to be in a reflection-dominated state, with \( N_H \gtrsim 1.5 \times 10^{24} \) cm\(^{-2} \) (ref. 24). Three years later, BeppoSAX observations found the source to be in a Compton-thin state53, implying a change in column density of \( \Delta N_H \approx 10^{24} \) cm\(^{-2} \). Since then, this source has been observed repeatedly by all major X-ray telescopes, which confirmed further strong \( N_H \) variability on a wide range of timescales and column densities24,26,27.

The first large study of a CO-AGN sample was carried out in the late 1990s: by studying \( \sim 50 \) AGN with multiple X-ray observations, equally split between obscured and unobscured, it was found that \( \sim 70\% \) of the objects show variable \( N_H \) on timescales of months to years54. A dedicated study of 25 narrow-line (type 2) AGNs55, collecting X-ray observations spanning timescales from months to several years, found that 22 sources (that is, nearly 90%) showed large-amplitude \( (\sim 20\%\text{–}100\%) \) variations in their \( N_H \). For a subsample of 11 objects with at least five X-ray observations, the typical variation timescales were found to be shorter than several months, with the obscuring material varying by \( \Delta N_H \approx 10^{25} \text{–}10^{26} \) cm\(^{-2} \). These studies confirmed the importance and high occurrence of CO events in nearby AGNs.

### The origin of CO events

While the most widely accepted explanation for CO events is related to intrinsic column-density variability, due to clouds moving in and out the line of sight (see ‘Eclipses’ section), several additional explanations have been proposed over the years. One such scenario is that the observed \( N_H \) changes are driven by changes in the ionization state of the material (see ‘Changes in the ionization state of the obscuring gas’ section), associated with an increase or decrease of the intrinsic AGN luminosity. In some other cases, CO events have been instead attributed to powerful AGN outflows (see ‘Outflows’ section). The most extreme CO events, where the AGN goes from (to) a transmission-dominated (from) a reflection-dominated state in the X-ray (that is, \( \Delta N_H \approx 10^{24} \) cm\(^{-2} \)), could be associated with a switch off/on of the AGN (see ‘Switch off/on of the central engine’ section). We briefly discuss each of these possible scenarios, and in Supplementary Section 2 we discuss in detail the current understanding regarding the location of the dynamic absorbers.

### Eclipses

Eclipses of the X-ray source are probably one of the most common causes of CO events. This was initially suggested based on the detection of rapid (that is, a few hours timescale56) variations of column density in nearby AGNs, and then confirmed by the observation of covering and uncovering events. A Chandra monitoring campaign of NGC 1365, with six observations carried out over 10 days, found that the source was first in a Compton-thin state, then showing a reflection-dominated X-ray spectrum two days later57. Subsequent observations found that the source was back to its initial, Compton-thin state. A continuous 5-day XMM-Newton monitoring campaign of NGC 1365 recorded the uncovering of the central X-ray source58. The source was in a reflection-dominated state for the first 1.5 days of the campaign, then showed an ~10-hours-long increase in flux, followed by a rather symmetric decrease. The X-ray spectral analysis showed that the increase in flux was due to a decrease of the column density, with the nuclear source being less obscured for several hours. The frequency of these events strongly argues in favour of the clumpy nature of the obscurer in NGC 1365. Long X-ray observations of other objects (for example, SWIFT J2127.4+5654 by ref. 31 and Mrk 766 by ref. 32) allowed to detect the transit of clouds with \( N_H \approx 10^{24} \text{–}10^{25} \) cm\(^{-2} \) on timescales of a few hours.

The aforementioned X-ray facilities, operating at energies \( E \lesssim 10 \) keV, cannot observe and identify \( N_H \) transitions of \( \sim 3 \times 10^{25} \text{–}10^{27} \) cm\(^{-2} \). The advent of the Nuclear Spectroscopic Telescope Array (NuSTAR), with its novel focusing capabilities in the hard X-ray band (\( \sim 10 \) keV), has opened a new window to study obscured AGNs, allowing to detect and characterize the absorption properties of a growing number of AGNs and to discover new CO-AGNs59. A joint XMM-Newton and NuSTAR campaign of the reflection-dominated AGN NGC106860 carried out in 2014 and 2015 found a transient excess in the hard X-ray band. This event was associated with a temporary decrease of the obscuring material, from \( N_H \approx 10^{25} \) cm\(^{-2} \) to \( N_H \approx 6.7 \times 10^{24} \) cm\(^{-2} \). This allowed, for the first time, to observe the primary X-ray continuum from the AGN in this object. Mid-infrared observations carried out before and after the X-ray event showed that the intrinsic, accretion-driven radiation from the source did not change during the transient event59, thus confirming that it was due to a change in the
line-of-sight column density. A follow-up NuSTAR campaign identified two additional CO events\(^26\): one unveiling (\(\Delta N_{\text{H}} \approx 1.8 \times 10^{24} \text{ cm}^{-2}\)) and one eclipsing (\(\Delta N_{\text{H}} \geq 2.4 \times 10^{24} \text{ cm}^{-2}\)) the X-ray source, thus confirming that the obscuring medium in NGC 1068 is rather dynamic (Fig. 2b).

Eclipses of the X-ray source can be used to put constraints on the location of the clouds producing the variable obscuration (Supplementary Section 2) and to infer the size of the X-ray corona. This can be done assuming that the clouds are moving in a Keplerian orbit around the SMBH, and that the size of the obscuring cloud is larger than (or consistent with) that of the X-ray source. In the case of NGC 1365, it was found that the size of the X-ray source is <10\(^{11}\) cm, corresponding to a few gravitational radii\(^27,28\). Similar scales were also derived for Mrk 766\(^29\) and SWIFT J2127.4+5654\(^30\). Interestingly, the X-ray coronae sizes obtained through this approach are consistent with those obtained by micro-lensing studies\(^30\).

**Changes in the ionization state of the obscuring gas.** An increase of the AGN luminosity could lead to an enhancement in the ionization state of the obscuring material, making it more transparent to X-ray radiation, which would in turn lead to an apparent decrease of the line-of-sight column density. This was one of the first explanations proposed for the \(N_{\text{H}}\) variations observed in NGC 4151\(^30\). For NGC 1365, it was argued that a change of two orders of magnitude in intrinsic AGN luminosity was required to explain the \(N_{\text{H}}\) variations between some of the observations\(^30\). However, such a strong luminosity variation was not observed. In general, this explanation does not appear to be viable for most CO-AGN events, as they usually do not show large variations of their bolometric luminosity associated with the CO events.

**Outflows.** While most objects discussed so far show variations of neutral absorption, in some cases, and particularly in unobscured/ type 1 AGNs, it has been found that the X-ray spectrum is strongly affected by variable ionized absorbing gas along the line of sight. Such absorbers are associated with outflows, which are common in AGNs, and have been routinely detected though absorption troughs both in the X-ray and optical/UV regimes\(^9,24\). The ionization properties of such absorbers can also be used to infer their distance (Supplementary Section 2). An interesting example of an outflow-driven event is the type 1 AGN NGC 5548, in which an intensive multi-wavelength monitoring campaign carried out in 2013 showed a clear CO event. A detailed study of the X-ray spectra revealed two obscuring components\(^40\): one with a low ionization level and a column density of \(\sim 10^{23} \text{ cm}^{-2}\) covering 86% of the X-ray source, and another one almost neutral, with a higher column density (\(< 10^{23} \text{ cm}^{-2}\) and smaller covering factor (\(\sim 30\%\)). The simultaneous UV spectroscopy allowed to observe broad absorption lines due to the low-ionization component, which showed that the material was outflowing with velocities of up to \(\sim 5,000 \text{ km s}^{-1}\). This event, which lasted several years, was ascribed to a wind from the accretion disk extending beyond the BLR. A similar obscuration event was later found in NGC 3783\(^31\). This event lasted about 1 month, with material partially obscuring the central source with a column density of \(\sim 10^{23} \text{ cm}^{-2}\), and outflowing with a velocity of a few 1,000 \text{ km s}^{-1}\. An analysis of previous X-ray observations of this source identified several additional CO events\(^32\). Dedicated campaigns have recently found similar CO events in other nearby AGN, such as NGC 3227\(^33\) and Mrk 817\(^34\). Some of these campaigns have also been able to observe the outflows obscuring the accretion disk\(^34\), and might be able in the future to shed light on the interplay between the accretion disk and the outflows. It should be noted that low signal-to-noise ratio and spectral resolution X-ray observations could sometimes mistakenly associate spectral changes due to outflowing ionized absorbers to eclipses from neutral material.

**Switch off/switch on of the central engine.** In addition to the scenarios discussed above, at least in some cases the dramatic changes observed in the X-ray spectral appearance of AGNs could be directly related to changes in the (intrinsic) X-ray luminosity\(^44\). If the accretion power of an AGN decreases rapidly, the primary X-ray continuum (that is, the power-law component) would also decrease. However, the reprocessed X-ray radiation, produced by material on scales of \(\geq 0.1-1\) pc, would react more slowly to changes in the irradiating X-ray flux, and could dominate the X-ray emission when the primary flux is at a low level. Therefore, for a certain time after a large drop in the intrinsic X-ray radiation, the source could be observed as a reflection-dominated AGN, and could be confused for a Compton-thick AGN. A re-increase of the accretion-powered radiation would then lead the source to again appear in the X-ray as a continuum-dominated AGN. This switch-off/switch-on process could (mistakenly) lead to identifying the source as a CO-AGN.
Two cases in which this mechanism could explain the spectral transitions observed in AGNs are those of NGC 2992,46,47 and the highly variable AGN NGC 405156. Both sources are switch-off AGNs that appeared reflection-dominated in several epochs of observation. Multiple X-ray observations of NGC 2992, starting from 1978, suggested that the X-ray emission faded over ~15–20 years, and then went back to its originally observed flux level in 199846. The X-ray spectrum of the type 1 AGN NGC 4051 was found to be reflection-dominated in a 1998 observation56, which was associated with a prolonged low-flux state48,49. In contrast, UGC 4203 was initially classified as a possible switch-off AGN50, while subsequent studies showed that the appearance of this AGN is probably affected by line-of-sight eclipses51. To clearly differentiate between switch-on/switch-off sources and sources with varying N\textsubscript{H}, it is fundamental to carefully analyse the long-term X-ray light curves and have a simultaneous broad spectral coverage, to best decipher the rich spectral information available in the X-ray.

Recent studies

Over the past two decades, repeated observations of nearby AGNs carried out by XMM-Newton, NuSTAR, Chandra, the Rossi X-ray Timing Explorer (RXTE), Swift and Suzaku found a growing number of CO transitions, showing that this phenomenon is rather common in AGNs52–54. These variations have been found by either repeated or very long observations. The best-studied CO-AGN, NGC 1365, has been the subject of several dedicated monitoring campaigns. These studies found variability of N\textsubscript{H} on timescales down to ~10\textsuperscript{2} cm\textsuperscript{-2} to ~10\textsuperscript{5} cm\textsuperscript{-2}. Similarly, rapid variations of N\textsubscript{H} = 10\textsuperscript{3}–10\textsuperscript{5} cm\textsuperscript{-2} down to timescales of ~4 hours and ~10–30 hours were observed in NGC 438855 and in NGC 415155. While typically these events are detected in AGNs showing obscuration signatures in the optical regime (type 1.8–2 sources), in a few instances they have also been observed in narrow-line Seyfert 1 (for example, Mrk 76653 and Swift J2127.4+565454) and type 1 (for example, ESO 323–G7756) sources, although their occurrence rate appears to be lower. Polarity studies52 of ESO 323–G77 have suggested it is observed at an intermediate inclination angle (~45°) with respect to the normal to the disk. This might imply that the detection of CO events in type 2 AGNs could be associated with lines of sight grazing the edge of the torus.

Several other studies have focused on searching for CO events in large samples of AGNs, to better understand their occurrence rates and links to other AGN and SMBH properties. A careful analysis of RXTE observations of ~40 nearby type 1 and Compton-thin type 2 AGNs uncovered 12 eclipse events in 8 of the sources52, with typical column densities of the variable absorber of ~10\textsuperscript{22}–10\textsuperscript{23} cm\textsuperscript{-2}. Analysing hardness-ratio light curves of 40 nearby AGNs with long XMM-Newton and Suzaku observations, it was found that spectral variability that could be ascribed to eclipses by BLR-like clouds was detected in all the cases where the length of the observations was sufficiently long53. More recently, N\textsubscript{H} variability was detected in 7 out of 20 objects observed by various X-ray satellites5, with variations in the range ~10\textsuperscript{21}–10\textsuperscript{23} cm\textsuperscript{-2}.

The structure of the BLR from X-ray eclipses

Studies of some of the most extreme CO events have shown that the density of the gas in the obscuring clouds tends to be high. For example, in the case of NGC 136528 and ESO 323–G7756, the clouds were found to have a density of ~10\textsuperscript{10} cm\textsuperscript{-3} and 0.1 × 10\textsuperscript{10}–8 × 10\textsuperscript{10} cm\textsuperscript{-3}, respectively. Similarly high densities were found for objects in which only a lower limit could be obtained54. These values are consistent with the typical density of BLR gas (~10\textsuperscript{10} cm\textsuperscript{-3}; ref. 59), and higher than what is expected for the dusty torus. Combined with the BLR-like distances of the transient obscurers (Supplementary Section 2), this strongly supports the idea that these CO-causing clouds are associated with those producing broad optical/UV lines.

As a large fraction of CO events could be caused by BLR clouds, X-ray spectroscopy can provide an important tool to shed light on this region. A crucial step forward in our understanding of the relation between BLR clouds and CO events came from a 300 ks Suzaku observation of NGC 136556, which found that the rapidly moving clouds in that system appear to have a cometary shape, with a high-density (~10\textsuperscript{10} cm\textsuperscript{-3}) core and an elongated (~10\textsuperscript{10} cm), lower-density, structure (Fig. 3). The opening angle of the tail was estimated to be small, that is, only a few degrees. Similarly, in Mrk 766, besides dense (~10\textsuperscript{10}–10\textsuperscript{10} cm\textsuperscript{-3}) neutral clouds, a tail of lower-density, highly ionized gas, causing blueshifted iron lines (Fe xxv and Fe xvii) with velocities Δv = 3,000–15,000 km s\textsuperscript{-1}, was also detected55. As the mass-loss rate of the cloud core material into the tail would imply their destruction within a few months, it was speculated that the clouds should be continuously replenished, possibly through outflows from the accretion disk56.

Changing-state AGNs

The accretion phase of SMBHs is expected to last ~10\textsuperscript{6}–10\textsuperscript{8} years57,62, during which the generally persistent accretion varies with typical emission amplitudes of tens of per cent58,59. A growing population of AGNs has been recently found to show much stronger flux variability,
over relatively short timescales, in both the optical44–47 and X-ray68 regimes. Some of these strong flux variations have been associated with CS transitions, with the (dis-)appearance of broad optical/UV emission lines and of the accretion-powered continuum emission being closely linked (Fig. 4).

**Early works**

One of the first observed CS transitions was found in 1975 from repeated observations of NGC 7603, where the broad Hβ line weakened by a factor of about 3 within 1 year70. Another CS event was identified in NGC 2992, one of the first candidate CO-AGNs (see ‘Switch off/switch on of the central engine’ section): early optical spectra published in the 1980s80 showed a type 1.9 spectrum, with a weak broad Hα and no detectable broad Hβ. By 1994, the source lost its broad Hα line73, transitioning to a type 2. The broad Hα line then reappeared 5 years later81. Interestingly, these variations were shown to be associated with the X-ray flux, which declined from a high state in the 1980s to reach a minimum in 1994, then recover during 199983. Several other known AGNs presented broad-line emission either disappearing (for example, 3C 390.3) or appearing (for example, NGC 3065). A small fraction of CS-AGNs have been found to undergo a full cycle, transitioning twice. For example, Mrk 1018 went from type 1.9 to type 1 within <5 years74, and then transitioned back to type 1.9 after 30 years75. NGC 1566 was observed to undergo several CS transitions between 1970 and 198576, in addition to the recent CS from type 1.9–1.8 to type 1.277.

**The advent of large surveys and statistical studies**

Over the past few years, large imaging and spectroscopic surveys allowed for many more CS-AGN identifications, greatly expanding the range of redshift (z) and key SMBH properties probed. One prominent example is the first changing-look quasar86, SDSS J0159+0033 (z = 0.31). The original Sloan Digital Sky Survey (SDSS) spectrum, taken in 2000, showed broad emission lines, which, however, disappeared by 2010, as observed through SDSS-III and re-confirmed during 201487. Several additional studies pursued a similar approach, systematically searching the (repeated) spectroscopy of SDSS and other spectroscopic surveys, and revealing a growing number of CS-AGNs82,83. In most such studies, the identification of CS events is based on drastic changes in the Hx and Hβ lines in spectra that are taken several years apart. At higher redshifts (z ≥ 1.5), CS-AGNs were identified based on the Mg II λ2798, C IV λ1549 and other (rest-frame) UV broad emission lines88–90. These emission lines probe somewhat different regimes of the variable ionizing AGN continuum and/or the BLR, and may thus provide invaluable, complementary insights regarding the nature of extreme AGN variability91. For example, the peculiar variability properties of Mg II λ279892, including its persistence in spectra that show weak (or no) other AGN indicators93, can be interpreted as recently turned-off AGNs94, where the Mg II line is not as responsive to the CS event as the Balmer lines95, reminiscent of some reverberation mapping results96.

Another example of this behaviour is IES 1927+65497, where the appearance of a blue continuum was followed by the appearance of broad Balmer emission lines, while neither Mg II nor C IV were detected.

The samples obtained with such spectroscopically focused CS-AGN searches can already provide some insights regarding their occurrence rates and the typical key properties for AGNs that experience CS transitions. Re-observing 102 local (0.02 ≤ z ≤ 0.1) broad-line AGN with previous SDSS spectroscopy, it was found98 that ~38% of the sources had changed spectral (sub-)classification, and that in ~3% of the sources the broad Hβ disappeared completely, within ~3–9 years. A spectroscopic effort to re-observe extremely variable SDSS quasars (showing Δ(g) > 1 mag in <15 years) identified 17 robust CS-AGNs among 130 carefully selected candidates99. Another search, within SDSS-IV repeated spectroscopy (and no photometric pre-selection)100 resulted in a total of 19 (15 newly identified) CS-AGNs, out of a parent sample of ~64,000 broad-line quasars. This translates to a significantly lower occurrence rate of ~0.03%. A rate of 0.7–6.2% on 10–25-year timescales was recently derived for a hard X-ray selected sample of nearby AGN101. The discrepancy in occurrence rate may be attributed not only to the different search methods (see also below) but also to the well-known anti-correlation between AGN luminosity and variability amplitude102,103. Some of these relatively large, spectroscopy-led samples of CS-AGNs, for which some form of comparison samples can be constructed, suggest that CS-AGNs have preferentially relatively low Eddington ratios104,105. This, however, should be treated with caution, as such studies may be subject to various observational biases (see below).

As CS events are typically associated with drastic changes in both the optical and X-ray fluxes (see ‘X-rays’ section), time-domain imaging surveys can be a powerful tool to identify candidate highly variable AGNs that can then be spectroscopically confirmed as CS-AGNs. One of the first CS-AGN events to be identified by this approach was NGC 2617, for which the All-Sky Automated Survey for SuperNovae (ASAS-SN)106 identified a substantial flux increase in 2013. Spectroscopic follow-up showed that the source, originally classified as a type 1.8 AGN in 2003, had transitioned to type 1107. Some of these surveys have discovered extremely peculiar objects, such as IES 1927+65498, the first source in which the CS transition was clearly temporarily resolved. This source, a known nearby AGN that historically showed no broad emission lines and no X-ray obscuration99, underwent an outburst at the end of 2017, which was detected by ASAS-SN. Intensive spectroscopic follow up showed the source first developing a blue, quasar-like continuum, then showing the appearance of broad Balmer lines109 (Fig. 4c). Photometric surveys have also found cases where low-luminosity Low-Ionization Nuclear Emission-line Regions (LINERs) transitioned to brighter, broad-lined AGN110,111.

The study of infrared variability, primarily enabled by repeated all-sky Wide-field Infrared Survey Explorer (WISE) imaging, has proven to be an useful approach to detect rapidly varying AGNs. Among the >4 million AGNs identified with WISE112, about 700 (0.015%) showed strong variability, and some of those were indeed associated with
Fig. 4 | Light curves and spectra of CS-AGNs showing an emergent BLR. a, SDSS (black diamonds), Panoramic Survey Telescope and Rapid Response System (Pan-STARRS, PS1, blue triangles) and Catalina Real-Time Transient Survey (CRTS, red dots) light curves (in modified Julian date or MJD) in the g band. b, SDSS (red) and Baryon Oscillation Spectroscopic Survey (BOSS, black) spectra, corresponding to the epochs indicated by the vertical dotted lines in a. The lower panels show the flux difference ($|\Delta F_{\lambda}|$) between the two spectra, together with the best-fit power-law $F_{\nu} \propto \nu^{\beta}$, with the red-dashed curve showing a power law with $\beta = 1/3$, as expected for a standard thin disk. c, Transition from a type 2 AGN (bottom) to a type 1 AGN in 1ES 1927+654, with an intermediate stage of a blue-continuum-dominated emission. The inset shows the evolution of the H$\alpha$ line. The pre-outburst spectrum shown is from ref. 150. Panels reproduced with permission from: a, b, ref. 80, Oxford Univ. Press; c, ref. 91, IOP.
In a study of the optical/UV outburst that led to the 2013 CS outburst, Mrk 590 showed correlated radio and optical/UV/X-ray variability. In addition, a weak radio jet could be the by-product of the recurring AGN activity. Mrk 1018, the radio emission decreased by ~20% during the type 1.9 dimming phase (2016–2017). Radio observations of the UV/optical-flaring AGN IES 1927+654 have revealed a dimming, by a factor of about 4, of the core radio component during the CS event, followed by a re-brightening. In this case, the radio-to-X-ray flux ratio continuously increased during the CS event. A study of a sample of CS-AGN at z < 0.83 found that these objects are unlikely to be more active in the radio than normal AGNs.

**CS events are generally powered by accretion not by obscuration**

The idea that (most) CS events can be attributed to changes in the level of obscuration of the BLR has been generally discarded by numerous lines of evidence, which thus promoted the view that most CS events are driven by changes in the intrinsic AGN continuum radiation.

Specifically, the challenges for the obscuration-driven scenario include the following. (1) The long timescales (≥10 years) that would be needed for a dusty cloud to efficiently cover the BLR, assuming reasonable cloud velocities. (2) The absence of reddening signatures in the dim-state optical spectra (see, however, ref. 117). (3) The observation of the optical broad lines appearing in IES 1927+654 about two to three months after the sudden appearance of a blue continuum. (4) The lack of obscuration in the X-ray for sources in which the broad lines are not clearly observed. Prominent examples of this include IES 1927+654 and Mrk 590. (5) The lack of a clear difference in \( E(B-V)/N_H \) between CS-AGNs and normal (persistent) AGNs. (6) The detection of rapid infrared variability (see 'Infrared' section), specifically the identification of infrared flux drops in several sources that exhibited Hα or Hβ disappearance. The infrared-emitting region is too large to be obscured on timescales of ≥10 years (similarly to the BLR mentioned above), and—importantly—the radiation at these mid-infrared wavelengths is much less affected by dust obscuration (compared with the optical/UV regime). (7) The correlation between radio and optical/UV (and/or X-ray) variability observed in a few objects (see 'X-rays' and 'Radio' sections). (8) The low levels of optical variability.
transitions in the optical regime. Future high-cadence spectroscopic studies may reveal more events of this type. Otherwise, these few cases remain examples of the exception rather than the rule.

Depending on the origin of the BLR, a change in the accretion flow (or rate) could either dramatically transform the BLR or change its ionization properties. First, the line emission from a pre-existing BLR is expected to respond to any (strong) ionizing continuum variability; CS events could thus be regarded as the most extreme cases of BLR reverberation, where it essentially turns on/off (following the light-travel lags). Second, it has been proposed that the BLR could be created by outflows originating from the accretion disk (or rate) could either dramatically transform the BLR or change its ionization properties. First, the line emission from a pre-existing BLR is expected to respond to any (strong) ionizing continuum variability; CS events could thus be regarded as the most extreme cases of BLR reverberation, where it essentially turns on/off (following the light-travel lags). Second, it has been proposed that the BLR could be created by outflows originating from the accretion disk. In this framework, the disappearance of broad optical/UV lines in CS-AGNs would arise straightforwardly from a strong decrease in the accretion rate in, and thus the mass outflow rate from, the disk.

**The origin of CS transitions**

Many of the scenarios proposed to explain CS events can be roughly divided into two main categories: instabilities in the (globally stable) accretion disk (‘Disk instabilities’ section), which could lead to changes in the emission properties of the accretion flow; and major accretion disk perturbations (‘Major disk perturbations’ section), such as stellar tidal disruption events (TDEs). It is possible that these two different types of mechanism could be at work in different CS events. A detailed discussion of the timescales involved in several
of the mechanisms mentioned in this section can be found in Supplementary Section 3.

**Disk instabilities.** Disk instabilities can be triggered by various processes, and can thus occur over a range of timescales. One possibly relevant mechanism for CS-AGNs is the thermal instability\(^{117}\), associated with changes in the surface density of the disk, driven by changes in opacity, which could lead to large (though localized) variations in temperature. The magnetorotational instability\(^{118}\) could also lead to changes in the local heating on thermal timescales. It has been shown\(^{119}\) that, in the case of Mrk 1018, the disappearance/appearance of the broad optical lines is directly related to the absence/presence of a strong soft X-ray excess at $\lesssim 2$ keV (Fig. 5a,b). Such a component, possibly associated with a warm Comptonizing material, could extend to the UV, and be responsible for most of the ionizing photons that create the broad emission lines. In Mrk 1018, the Eddington ratio goes from $\lambda_{\text{Edd}} = 8 \times 10^{-2}$ to $\lambda_{\text{Edd}} = 6 \times 10^{-3}$ during the event that leads to the disappearance of the broad lines. At the same time, the $\approx 2$ keV emission dropped by only a factor of about 7, while the soft X-ray excess decreases of a factor of $\approx 60$. Qualitatively similar events were observed in other CS-AGNs\(^{120}-^{122}\). This spectral hardening could be similar to the soft-to-hard state transitions observed in black-hole binaries\(^ {123,124}\), associated with the hydrogen ionization disk instability, where the inner disk `puffs up' and transitions into an advection-dominated accretion flow at $\lambda_{\text{Edd}} \lesssim 0.02$. These state transitions would therefore produce large variations of the amount of ionizing radiation emitted by the AGN. A consistent behaviour was also found\(^ {125}\) by studying the relation between the optical-to-X-ray spectral index ($\alpha_{\text{ox}}$) and $\lambda_{\text{Edd}}$, which showed similarities to what is observed in black-hole binaries, including an inversion of the $\alpha_{\text{ox}}$--$\lambda_{\text{Edd}}$ correlation at $\lambda_{\text{Edd}} = 10^{-2}$. Several recent studies have indeed suggested that CS-AGN occur at this regime of Eddington ratios\(^ {126}\). The timescale associated with such transitions would be the viscous timescale ($\tau_{\text{vis}}$, equation (10) in Supplementary Section 3), which is considerably longer than the observed timescales of CS events. However, as radiation pressure in AGNs is more important than in binaries\(^ {127}\), the sound speed in the disk would be higher, leading to a decrease in $\tau_{\text{vis}}$. Including magnetic pressure would further increase the sound speed and decrease the expected timescales. A similar effect would be expected in thicker disks, which could be caused by several mechanisms (as outlined in Supplementary Section 3).

Another viable mechanism for CS events is the propagation of a cooling front in an inflated accretion disk, associated with a sudden change in the magnetic torques in the innermost regions of the accretion flow\(^ {128,129}\). Magneto-hydrodynamical instabilities could cause the torques to decrease, leading to an outwards-propagating cold front, which would decrease the emitted optical/UV radiation. At some point, a heating front is expected to start propagating inwards, leading to a re-brightening\(^ {130}\). The inflated inner disk would have a larger aspect ratio (i.e. a ratio between the height and radius of the disk $H/R = 0.2$) than typically assumed for standard accretion disk\(^ {131}\), which would lead to considerably shorter timescales (see equation (9) in Supplementary Section 3), consistent with those observed in some CS events. This model was shown to explain the fading and re-brightening of the UV continuum and of the broad emission lines in SDSS J1100−0053\(^ {132}\). There are other suggestions for how advection- and radiation-pressure-dominated regions in the inner disk may drive instabilities, relevant for CS transitions, even in sources accreting at Eddington rates of a few per cent. Specifically, instabilities are expected to develop in a narrow region that links the inner advection-dominated-accretion-flow-like part of the accretion flow and the outer, thin disk, and could explain the recurrent CS events observed in objects such as NGC 1566 and NGC 4151\(^ {133}\). A sudden change of polarity of the magnetic flux advected onto the SMBH could also lead to a CS event, triggering an increase in the UV/optical flux while at the same time destroying the X-ray corona\(^ {134}\). For a magnetically supported and highly viscous ($\alpha = 1$) disk, these changes are expected to occur on short timescales ($\approx 1$ year), consistent with the events observed in IES 1927+654.

**Major disk perturbations.** Some CS-AGNs could be powered by the tidal disruption of a star passing near a SMBH. This explanation was proposed for the changing-look quasar SDSS J0159+0033\(^ {135}\), which, after the outburst that caused the CS event, showed a decline in flux consistent with the $t^{-3/2}$ trend expected for TDEs (and supported by some observations\(^ {136}\)). The estimated virial black hole mass of this object ($\approx 10^8 M_\odot$; ref. 78) is considerably higher than what is observed in, and expected for, typical TDEs. This could pose a problem, as the tidal radius ($r_{\text{tid}}$), that is, the radius at which a star of mass $M$ and radius $R$ would probably be disrupted, is inversely proportional to $M_{\text{BH}}$:

$$r_{\text{tid}} \approx 2.2 r_g \left( \frac{M}{M_\odot} \right)^{-1/3} \left( \frac{R}{R_\odot} \right) M_{\text{BH}}^{-2/3},$$

(1)

where $r_g$ is the gravitational radius. Therefore, a tidal disruption would be detected only if the star is not too compact and the SMBH is not too massive. For SDSS J0159+0033, the tidal radius would be expected to be at only a few $r_g$. It was, however, argued that the virial BH mass of SDSS J0159+0033 could be appreciably overestimated, possibly due to the contribution of the stellar debris to the Ha emission line\(^ {137}\). Another explanation may involve a black hole with a non-zero spin, which would lead to a smaller ergosphere and allow for (observable) TDEs with smaller $r_{\text{tid}}$ (ref. 138). TDEs that occur in, and interact with, an already-active SMBH were also invoked to explain the disappearance and reappearance of the X-ray corona\(^ {139,140}\), the strong blackbody component\(^ {141,142}\) and the peculiar behaviour of the broad optical lines\(^ {143}\) seen in IES 1927+654.

Some models suggest that the occurrence rate of TDEs would be higher in (persistently accreting) AGNs\(^ {144}\), and that TDEs in AGNs could be associated with the presence of stars within the accretion flow itself\(^ {145}\). Recent simulations\(^ {146}\) demonstrated how the debris stream of the tidally disrupted star would hit an accretion disk, disrupting the gas in the disk and further depleting a large fraction of the angular momentum of the disk gas (including through shocks). This, in turn, would rapidly increase the accretion rate of material through the inner regions of the disk, strongly affecting the UV/optical emission\(^ {147}\), and may lead to the disappearance of the X-ray corona. As the inner disk is replenished, the corona would be `reignited'. If the gas pressure falls sharply from the outer disk to the inner disk, then magnetic loops could

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### Table 1 | Probing different regions of accreting SMBHs with CL-AGNs

| Region | CL-AGNs |
|-------|---------|
| X-ray corona | Size\(^ {127}\) ('Eclipses’ section) |
|          | Creation\(^ {148}\), evolution with changes in accretion\(^ {105}\) (X-rays’ section) |
| Accretion disk | Interplay disk/outflows ('Outflows’ section) |
|          | Variability timescales (Supplementary Section 3), mechanisms triggering instabilities and perturbations (The origin of CS transitions’ section) |
| Broad-line region | Physical and kinematical properties of the clouds\(^ {132,149}\) (The structure of the BLR from X-ray eclipses’ section) |
|          | Creation and evolution\(^ {106}\) (CS events are generally accretion not obscurcation’ section) |
| Torus | Physical and kinematical properties of the clouds\(^ {133}\) ('Recent studies’ section) |
|        | Size and dust replenishment\(^ {150}\) ('Infrared’ section) |

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pull the gas, allowing it to spiral inwards within tens of disk orbital timescales (equation (7) in Supplementary Section 3), roughly in agreement with timescales observed for IES 192.7+654 We note that detailed numerical studies of such processes are still scarce and large parts of the parameter space are yet to be explored.

Other mechanisms proposed to explain CS events include the tidal interaction between disks in binary SMBHs, and the interaction between the disk and a recoiling SMBH. The latter explanation has been proposed for Mrk 1018, with the recoiling SMBH having a very eccentric orbit and perturbing the accretion flow with a period of about 29 years. Finally, stellar-mass point perturbers in the disk (that is, stars or stellar-mass BHs) could cause extreme mass-ratio inspiral events or changes in the accretion flow, triggering (potentially recurring) CS events.

The bright near future

While CO and CS events are generally very different in nature, both types of transition allow us to probe the close vicinity of accreting SMBHs (Table 1). With the advent of large photometric (Vera Rubin Observatory4) and spectroscopic (SDSS-V15, 4MOST16) optical surveys, as well as wide-field surveys in the X-rays (that is, with eROSITA17 and the Einstein Probe18) and the UV (for example, with ULTRASAT19), in the next few years a very large number of CS, CO and other yet unknown types of extreme variability event in AGNs will be identified and characterized. The large sample sizes and the well-defined nature of the surveys will allow us to better understand the physical mechanisms at play in these fascinating objects, and to make important progress in the topics of SMBH fuelling and more general accretion physics.

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