Cold, clumpy accretion onto an active supermassive black hole

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Cold, clumpy accretion onto an active supermassive black hole

Grant R. Tremblay1,2,‡, J. B. Raymond Oonk3,4, Françoise Combes5, Philippe Salome5, Christopher P. O’Dea6,7, Stefi A. Baum6,8, G. Mark Voit9, Megan Donahue9, Brian R. McNamara10, Timothy A. Davis1,2,4, Michael A. McDonald12, Alastair C. Edge13, Tracy E. Clarke14, Roberto Galván-Madrid15,2, Malcolm N. Bremer16, Louise O. V. Edwards1, Andrew C. Fabian17, Stephen Hamer5, Yuan Li18, Anaëlle Maury19, Helen Russell17, Alice C. Quillen20, C. Megan Urry1, Jeremy S. Sanders21, & Michael Wise3

Supermassive black holes in galaxy centres can grow by the accretion of gas, liberating energy that might regulate star formation on galaxy-wide scales1-4. The nature of the gaseous fuel reservoirs that power black hole growth is nevertheless largely unconstrained by observations, and is instead routinely simplified as a smooth, spherical inflow of very hot gas4. Recent theory5-7 and simulations8-10 instead predict that accretion can be dominated by a stochastic, clumpy distribution of very cold molecular clouds — a departure from the ‘hot mode’ accretion model — although unambiguous observational support for this prediction remains elusive. Here we report observations that reveal a cold, clumpy accretion flow towards a supermassive black hole fuel reservoir in the nucleus of the Abell 2597 Brightest Cluster Galaxy (BCG), a nearby (redshift \( z = 0.0821 \)) giant elliptical galaxy surrounded by a dense halo of hot plasma11-13. Under the right conditions, thermal instabilities can precipitate from this hot gas, producing a rain of cold clouds that fall toward the galaxy’s centre14, sustaining star formation and a kiloparsec-scale molecular nebula that inhabits its core15. The observations show that these cold clouds also fuel black hole accretion, revealing ‘shadows’ cast by the molecular clouds as they move inward at about 300 kilometres per second towards the active supermassive black hole in the galaxy centre, which serves as a bright backlight. Corroborating evidence from prior observations16 of warmer atomic gas at extremely high spatial resolution17, along with simple arguments based on geometry and probability, indicate that these clouds are within the innermost hundred parsecs of the black hole, and falling closer towards it.

We observed the Abell 2597 Brightest Cluster Galaxy (Fig. 1) with the Atacama Large Millimeter/submillimeter Array (ALMA), enabling us to create a three-dimensional map of both the location and motions of cold gas at uniquely high sensitivity and spatial resolution. The ALMA receivers were sensitive to emission from the \( J = 2 - 1 \) rotational line of the carbon monoxide (CO) molecule. CO(2-1) emission is used as a tracer of cold (~10 – 30 K) molecular hydrogen, which is vastly more abundant, but not directly observable at these low temperatures. The continuum-subtracted CO(2-1) images (Fig. 2) reveal that the filamentary emission line nebula that spans the galaxy’s innermost ~30 kpc (Fig. 1b) consists not only of warm ionised gas18-20, but cold molecular gas as well. In projection, the optical emission line nebula is cospatial and morphologically matched with CO(2-1) emission detected at a significance between \( \gtrsim 3\sigma \) (in the outer filaments) and \( \gtrsim 20\sigma \) (in the nuclear region) above the background noise level. The warm ionised nebula is therefore likely to have a substantial molecular component, consistent with results for other similar galaxies21. The total measured CO(2-1) line flux corresponds to a molecular hydrogen gas mass of \( M_{\text{H}_2} = (1.8 \pm 0.2) \times 10^9 M_\odot \), where \( M_\odot \) is the mass of the sun. The critical (minimum) density for CO(2-1) emission requires that the volume filling factor of this gas be very low, of order a few percent. The projected spatial coincidence of both the warm ionised and cold molecular nebulae therefore supports the long-envisioned hypothesis that the ionised gas is merely the warm ‘skin’ surrounding far colder and more massive molecular cores22,23, whose outer regions are heated by intense radiation from the environment in which they reside. Rather than a monolithic, kiloparsec-scale slab of cold gas, we are more likely observing a projected superposition of many smaller, isolated clouds and filaments.

The data unambiguously show that cold molecular gas is falling inward along a line of sight that intersects the galaxy centre. We know this because the ALMA beam cospatial with the millimetre continuum source, the radio core, and the isophotal centre of the galaxy reveals strong, redshifted continuum absorption (Fig. 3b), found by extracting the CO(2-1) spectrum from this central beam. This reveals at least three deep and narrow absorption lines (Fig. 3c), with redshifted line centres at \( \Delta \nu / \nu = \pm 2, \pm 3 \) (in the outer filaments) and \( \Delta \nu / \nu > 20 \) (in the nuclear region) above the background noise level. The warm ionised nebula is therefore likely to have a substantial molecular component, consistent with results for other similar galaxies21. The total measured CO(2-1) line flux corresponds to a molecular hydrogen gas mass of \( M_{\text{H}_2} = (1.8 \pm 0.2) \times 10^9 M_\odot \), where \( M_\odot \) is the mass of the sun. The critical (minimum) density for CO(2-1) emission requires that the volume filling factor of this gas be very low, of order a few percent. The projected spatial coincidence of both the warm ionised and cold molecular nebulae therefore supports the long-envisioned hypothesis that the ionised gas is merely the warm ‘skin’ surrounding far colder and more massive molecular cores22,23, whose outer regions are heated by intense radiation from the environment in which they reside. Rather than a monolithic, kiloparsec-scale slab of cold gas, we are more likely observing a projected superposition of many smaller, isolated clouds and filaments.

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† Einstein Fellow ‡ Rutherford Fellow
Figure 1 | A multiwavelength view of the Abell 2597 BCG. (a) Chandra X-ray, HST and DSS optical, and Magellan Hα+[NII] emission is shown in blue, yellow, and red, respectively (Credit: X-ray: NASA / CXC / Michigan State Univ / G.Voit et al; Optical: NASA/STScI & DSS; Hα: Carnegie Obs. / Magellan / W.Baade Telescope / U.Maryland / M.McDonald). (b) HST image of Lyα emission associated with the ionised gas nebula. (c) Unsharp mask of the HST far-ultraviolet continuum image of the central regions of the nebula. Very Large Array (VLA) radio contours of the 8.4 GHz source are overlaid in red.
because they cast ‘shadows’ along the line of sight as the clouds eclipse or attenuate about 20% (or about 2 mJy) of the millimetre synchrotron continuum source, which serves as a bright background (13.6 mJy at rest-frame 230 GHz). The synchrotron continuum is emitted by jets launched from the accreting supermassive (~3 x 10^9 M⊙) black hole in the galaxy’s active nucleus (Fig. 4). The absorbers must therefore be located somewhere between the observer and the galaxy centre, falling deeper into the galaxy at ~ +300 km s^{-1} toward the black hole at its core. This radial speed is roughly equal to the expected circular velocity in the nucleus, consistent either with a nearly radial orbit, or highly non-circular motions in close proximity to the galaxy’s core.

Gaussian fits to the spectral absorption features reveal narrow linewidths of c_v ≲ 6 km s^{-1}, which means the absorbers are more likely spatially compact, with sizes that span tens (rather than hundreds or thousands) of parsecs. The shapes of the absorption lines remain roughly the same regardless of how finely the spectra are binned, suggesting that the absorbers are likely coherent structures, rather than a superposition of many smaller absorbers unresolved in velocity space. If each absorption feature corresponds to one coherent cloud, and if those clouds roughly obey size-linewidth relations for giant molecular clouds in the Milky Way, they should have diameters not larger than ~ 40 pc. If in virial equilibrium, molecular clouds this size would have masses of order 10^5-10^6 M⊙, and if in rough pressure equilibrium with their ambient multiphase K environment they must have high column densities of order NH_2 ≈ 10^{22-24} cm^{-2} so as to maintain pressure support. The thermal pressure in the core of Abell 2597 is nearly three thousand times greater than that for the Milky Way, however, which means the absorbing clouds may be much smaller.

The absorbers have optical depths that range from 0.1 ≲ τ_{CO(2-1)} ≲ 0.3. The physical resolution of the ALMA data is larger than the synchrotron background source, which means that the optical depth is likely contaminated by an unresolved, additive superposition of both emission and absorption within the beam. Compact, dense cold clouds are nevertheless likely to be optically thick, which may mean they eclipse the continuum source with an optical depth of unity but a small covering factor of roughly 0.2. Especially when considering beam contamination by emission, the covering factor cannot be known with certainty, as this depends on the unknown geometry of the absorbing and emitting regions within the ALMA beam.

This geometry can be constrained, however, given existing Very Long Baseline Array (VLBA) radio observations at extremely high spatial resolution. These data resolve the J and K 5 GHz radio continuum source down to scales of 25 parsecs, revealing a highly symmetric, 100 pc-scale jet about a bright radio core (Fig. 4c). Just as we have found in cold molecular gas, inflowing warmer atomic hydrogen gas (HI) has previously been found in absorption against this pc-scale jet, corroborating prior reports of inflowing atomic gas at lower spatial resolutions. The inflow velocity of this gas matches that seen in our ALMA data. Remarkably, both the optical depth and linewidth of the warm atomic absorption signal varies dramatically across the jet, with a broad (c_v ≈ 310 km s^{-1}) component closely spatially coexisting with the core that is absent just ~ 20 pc to the northeast, where only a narrow (c_v ≈ 50 km s^{-1}) HI line is found at the same redshift. This effectively requires the inflowing atomic gas to be confined within the innermost ~ 100 pc of the black hole, as gas further out would give rise to an unchanging absorption signal across the compact jet. The infall velocity is the same as that for the cold molecular clouds seen in CO(2-1) absorption, which means they most likely stem from the same spatial region, within tens of parsecs of the accreting black hole.

This is further supported by the ALMA data itself. In emission, all gas around ~ +300 km s^{-1} that is conceivably available to attenuate the continuum signal is confined to the innermost 2 kpc about the nucleus (Fig. 4a,b). The radial dependence of molecular cloud volume number density within this region is uncertain, but probably steeper than r^{-1}, and likely closer to r^{-2} (Fig. 4b). This means that the chances of a random line of sight crossing will drop with increasing distance from the black hole. If the gas volume density goes as r^{-2}, a cloud 100 pc from the black hole is ten times more likely to cross our line of sight than a cloud at a galactocentric distance of 1 kpc. It would be exceedingly unlikely for three such clouds to cross our line of sight to the black hole were they spread over several kiloparsecs throughout the galaxy’s outskirts.

The data therefore serve as strong observational evidence for an inward-moving, clumpy distribution of molecular clouds within a few hundred parsecs of an accreting supermassive black hole. The infalling clouds are likely a few to tens of parsecs across and therefore massive (perhaps 10^5-6 M⊙ each). If they are falling directly toward the black hole, rather than bound in a non-circular orbit that tightly winds around it, they could supply an upper-limit accretion rate on the order of ~ 0.1 to a few M⊙ yr^{-1}, depending on the three dimensional distribution of infalling clouds. If most of the clouds are instead locked in non-circular orbits around the black hole, the fuelling rate would depend on the gas angular momentum, and the local supply of torques that might lessen it. Simulations suggest that such torques may be plentiful, as they predict a stochastic ‘rain’ of thermal instabilities that condense from all directions around the black hole, promoting angular momentum cancellation via tidal stress and cloud-cloud collisions. Even highly elliptical cloud orbits should therefore be associated with significant inward radial motions. The clouds might fall onto the accretion disc itself, or into a clumpy rotating ring akin to the ‘torus’ invoked in AGN unification models.

Cold accretion onto black holes has long been predicted by both theory and simulations, but it has not been definitively observed in a manner so stripped of ambiguity regarding the clouds’ proximity to a black hole. While no observation of a single galaxy can prove this theoretical prediction to be definitively true, the combined ALMA and VLBA dataset for Abell 2597 enable a uniquely unambiguous observation of molecular clouds that are either directly associated with black hole growth, or are soon about to be. The result augments a small but growing set of previously published molecular absorption systems in which black hole proximity is less well constrained. These could nevertheless be used to inform future systematic searches for cold black hole accretion across larger samples. Multi-epoch observations with ALMA might reveal shifts in the absorption lines, confirming their close proximity, and resolving cold black hole accretion as it evolves through time.

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2. McNamara, B. R. & Nulsen, P. E. J. Mechanical feedback from active
Figure 2 | ALMA observation of continuum-subtracted CO(2-1) emission in the Abell 2597 BCG. Emission is integrated from –600 to +600 km s\(^{-1}\) relative to the galaxy’s systemic velocity. Channels are binned to 40 km s\(^{-1}\). Only $\geq 3\sigma$ emission is shown. 8.4 GHz VLA radio contours are overlaid in black, and H\(\alpha\)+[N II] contours outlining the rough boundary of the ionised nebula are shown in grey. The nebula is slightly larger than the grey contours suggest: emission outside of this boundary is still part of a smooth, fainter distribution of cold gas, cospatial with similarly faint emission in the optical.
Figure 3 | ‘Shadows’ cast by molecular clouds moving toward the supermassive black hole. (a) Continuum-subtracted ALMA CO(2-1) spectrum extracted from a central 10 kpc region. Brackets mark CO(2-1) emission shown in panel (b), where 8.4 GHz radio contours are overlaid. The central radio contours have been removed to aid viewing of the continuum absorption, seen as the blue/black spot of ‘negative’ emission. (c) Continuum-subtracted CO(2-1) spectrum extracted from this region cospatial with the mm and radio core. Absorption lines are indicated in red.


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Mass Estimates. All molecular gas masses estimated in this letter caveat or ambiguity, the absorbing cold clouds are moving to real motion relative to the galaxy's stellar component. Without database). We are therefore certain that the reported redshift of template spectra cross-correlation of emission and absorption lines using galaxy \pm H_{31} CO(2-1) emission peaks. This frequency corresponds to transition from blue- to redshift. All CO(2-1) line velocities discussed systemic (stellar) velocity to be used as a 'zero point' marking the Interpretation of gas motions continuum data also features compact (\sim 1 kpc) extended emission \sim 0.0821). The ALMA correlator, \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \si
be roughly estimated by applying the virial relation,

\[
M_{\text{cloud}} \approx \frac{R_{\text{cloud}} \sigma_v^2}{G}
\]

\[
\approx \frac{20 \text{ pc} \times (6 \text{ km/s})^2}{4.302 \times 10^{-3} \text{ pc} \ M_\odot^{-1} \ (\text{km/s})^2}
\]

\[
\approx 1.7 \times 10^5 \ M_\odot,
\]

where \(R_{\text{cloud}}\) is the cloud radius (as roughly estimated above) and \(\sigma_v\) is its velocity dispersion (also as above).

CO(2-1) optical depths for the absorbers were estimated by assuming that

\[
I_{\text{total}} = I_{\text{continuum}} e^{-\tau_{\text{CO}(2-1)}},
\]

where \(I_{\text{total}}\) and \(I_{\text{continuum}}\) are the integrated intensities of the total (line plus continuum) and continuum-only signals, respectively, and \(\tau_{\text{CO}(2-1)}\) is the optical depth of the CO(2-1) absorption feature.

The stellar velocity dispersion of the BCG is \(\sigma_v = 220 \pm 19\) km s\(^{-1}\). Under the assumption of an isothermal sphere, the circular velocity should be \(\sim 300\) km s\(^{-1}\), (i.e., \(\sqrt{2} \sigma_v\)) which is roughly the line of sight velocity of the absorption features. The redshift of the absorption features is a significant fraction of this, which means they could be on a purely radial orbit (though their transverse velocity cannot be known with this single observation).

If our line of sight is representative, and therefore a ‘pencil beam’ sample of a three-dimensional spherical distribution of clouds, the total mass of cold gas contained within this distribution should go roughly as

\[
M \approx 10^6 M_\odot \times f_c \times \left(\frac{r}{1 \text{kpc}}\right)^2 \times \left(\frac{N_H}{10^{22} \text{cm}^{-2}}\right)
\]

where \(f_c\) is the covering factor and \(r\) is the radius of an imaginary thin spherical shell of molecular gas with column density \(N_H\). If such a shell had a covering factor of 1, a radius of 1 kpc, and a column density of \(10^{22}\) cm\(^{-2}\), then the total mass of molecular hydrogen contained within that shell would be roughly one billion solar masses. A column density in excess of \(10^{22}\) requires this distribution to be contained within a sphere of radius \(<< 1\) kpc, lest the total mass of molecular hydrogen in the galaxy be violated. If the characteristic column density is \(10^{23}\) cm\(^{-2}\), for example, this mass must be contained within a sphere of radius 300 pc, or else its total mass would exceed the \(\sim 1.8 \times 10^9 M_\odot\) present in the system.

**Code, software, and data availability.** The raw ALMA data used in this Letter are publicly available at the ALMA Science Archive, accessible here: https://almascience.nrao.edu/aq/ (search for project code 2012.1.00988.S). Codes that we have written to both reduce and analyse the ALMA data have been made publicly available here: https://github.com/granttremblay/Tremblay_Nature_ALMA_Abell2597. Reduction of the data as well as some simple modeling (e.g., fitting of Gaussians to lines) was performed using routines included in CASA version 4.2, available here: http://casa.nrao.edu/casa_obtaining.shtml. This research made use of Astropy (http://www.astropy.org), a community-developed core Python package for Astronomy.