Cold, clumpy accretion onto an active supermassive black hole

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Supermassive black holes in galaxy centres can grow by the accretion of gas, liberating energy that might regulate star formation on galaxy-wide scales1-3. 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 produce a rain of cold clouds that fall towards the galaxy’s centre14, sustaining star formation amid a kiloparsec-scale molecular nebula that is found at 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, 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 BCG (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. Such CO(2–1) emission is used as a tracer of the cold, clumpy accretion flow into the galaxy at about $300 \mathrm{km} \mathrm{s}^{-1}$ towards the black hole at its core. The observations reveal 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, 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.

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The continuum-subtracted CO(2–1) images (Fig. 2) reveal that the filamentary emission line nebula that spans the galaxy’s innermost $\sim 30 \mathrm{kpc}$ (Fig. 1b) consists not only of warm ionized gas18-20, but also cold molecular gas. In projection, the optical emission line nebula is co-spatial 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 ionized 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 $M_\text{H}_2 = (1.8 \pm 0.2) \times 10^7 M_\odot$, 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 the order of a few percent. The projected spatial coincidence of both the warm ionized and cold molecular nebulae therefore supports the long-envisaged hypothesis that the ionized 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 to be 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 that is co-spatial 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 $+240, +275$, and $+335 \mathrm{km} \mathrm{s}^{-1}$ relative to the systemic (stellar) velocity of the galaxy, all within an angular (physical) region of $0.715'' \times 0.533''$ (1 kpc $\times 0.8$ kpc).

These absorption features arise from cold molecular clouds moving towards the centre of the galaxy, via either radial or inspiralling trajectories. They manifest as continuum absorption because they cast ‘shadows’ along the line of sight as the clouds eclipse or attenuate about $\sim 20\%$ (or about 2 mJy) of the millimetre synchrotron continuum source, which serves as a bright backlight (13.6 mJy at rest-frame 230 GHz). The synchrotron continuum is emitted by jets launched from the accreting supermassive ($\sim 3 \times 10^8 M_\odot$; ref. 13) 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 about $+300 \mathrm{km} \mathrm{s}^{-1}$ towards the black hole at its core.

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LETTER
This radial speed is roughly equal to the expected circular velocity in the nucleus, consistent either with a nearly radial orbit, or with highly non-circular motions in close proximity to the galaxy's core.

Gaussian fits to the spectral absorption features reveal narrow linewidths of $\sigma_v \lesssim 6\, \text{km}\,\text{s}^{-1}$, which means the absorbers are more probably 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 probably 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 $\sim 40\, \text{pc}$. If in virial equilibrium, molecular clouds this size would have masses of the order of $10^5$–$10^6\, M_\odot$, and if in rough pressure equilibrium with their ambient multiphase ($10^3$–$10^7\, \text{K}$) environment, they

must have high column densities of the order of $N_{\text{H}} \approx 10^{22}$–$10^{24}\, \text{cm}^{-2}$ so as to maintain pressure support. The thermal pressure in the core of Abell 2597 BCG is nearly $3,000\, \text{times}$ greater than that for the Milky Way, however, which means the absorbing clouds may be much smaller.

The absorbers have optical depths in the range $0.1 \lesssim \tau_{\text{CO}(2–1)} \lesssim 0.3$. The physical resolution of the ALMA data is larger than the synchrotron background source, which means that the optical depth is probably 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 1.3 GHz and 5 GHz radio continuum source down to scales of 25 pc, 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 (H I) has previously been found in absorption against this parsec-scale jet, corroborating prior reports of inflowing atomic gas at lower spatial resolutions. The inflow velocity of this gas matches that seen...
inward-moving, clumpy distribution of molecular clouds within a few hundred parsecs of an accreting supermassive black hole. The result augments a small but growing set of known molecular absorption systems\(^9\)–\(^2_\text{9}\) whose black hole proximity is less well constrained. The infalling clouds in Abell 2597 BCG are probably a few to tens of parsecs across and therefore massive (perhaps \(10^8–10^9\) \(M_\odot\) each). If they are falling directly towards the black hole, rather than bound in a non-circular orbit that tightly winds around it, they could supply an upper-limit accretion rate of the order of \(\sim 0.1\) to a few solar masses per year, 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\(^9,16,14\) 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 disk itself, or into a clumpy rotating ring akin to the ‘torus’ invoked in AGN unification models\(^5\).

Online Content Methods, along with any additional Extended Data display items and Source Data, are available in the online version of the paper; references unique to these sections appear only in the online paper.

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METHODS

Observations, data reduction, and analysis. The new ALMA data presented in this paper were obtained in Cycle 1 with the use of 29 operational antennae in the 12 m Array. ALMA’s Band 6 heterodyne receivers were tuned to a frequency of 213 GHz, sensitive to the J = 2–1 rotational line transition of carbon monoxide at the redshift of the Abell 2597 BCG (z = 0.0821). The ALMA correlator, set to Frequency Division Mode (FDM), delivered a bandwidth of 1.875 MHz per (baseband) with a 0.488 MHz channel spacing, for a maximum spectral resolution of about 2 km s\(^{-1}\). One baseband was centered on the CO(2–1) emission line, while the other three basebands sampled the local continuum. Maximum antenna baselines extended to ~1 km, delivering an angular resolution at 213 GHz of ~0.3" within a ~28" primary beam (field of view). ALMA observed the Abell 2597 BCG, located at RA 23h 25m 20s, dec. –12° 07’ 38” (J2000), for a total of ~3 h over three separate scheduling blocks executed between 17 and 19 November 2013. The planet Neptune and quasars J2258 – 2758 and J2331 – 1556 were used for amplitude, flux, and phase calibration. The data were reduced using CASA version 4.2 with calibration and imaging scripts kindly provided by the ALMA Regional Centers (ARC’s) in both Garching, Germany and Manchester, UK. Beyond the standard application of the phase calibrator solution, we iteratively performed self-calibration of the data using the galaxy’s own continuum, yielding a ~14% decrease in RMS noise to a final value of 0.16 mJy per 0.715” x 0.533” beam per 40 km s\(^{-1}\) channel. There is effectively no difference in CO(2–1) morphology between the self-calibrated and non-self-calibrated data cubes. Measurement sets were imaged using ‘natural’ visibility weighting and binning to either 5 km s\(^{-1}\), or 40 km s\(^{-1}\), as indicated in the figure legends. The figures presented in this Letter show only continuum-subtracted, pure CO(2–1) line emission. The rest-frame 230 GHz continuum observation is dominated by a bright (13.6 mJy) point source associated with the AGN (detected at ~2000s), serving as the bright ‘background’ against which the continuum absorption features presented in this Letter were observed. The continuum bandwidth is a factor of 38 narrower than the CO(2–1) extended emission at ~10" that extends along the galaxy’s dust lane, to be discussed in a forthcoming paper.

Adoption of a systemic velocity. Interpretation of gas motions relative to the stellar component of a galaxy requires adoption of a systemic (stellar) velocity to be used as a ‘zero point’ marking the transition from blue- to redshift. All CO(2–1) line velocities discussed in this Letter are set relative to 213.04685 GHz, where observed CO(2–1) emission peaks. This frequency corresponds to 12CO(2–1) (rest-frame emission peaks. This frequency corresponds to 12CO(2–1) (rest-frame) and continuum-only signals, respectively, and CO(2–1) is the optical depth of the CO(2–1) absorption feature.

The stellar velocity dispersion of the BCG is 33 \(\sigma_v\) = 60 km s\(^{-1}\) (that is, \(\sigma_v\) = 63 \(\pm 2\) km s\(^{-1}\)). The uncertainty means they could be on a nearly radial orbit (though their transverse velocity cannot be known with this single observation).

Estimating physical properties of the redshifted absorbing molecular gas. We have estimated a rough upper-limit size of the absorbing clouds assuming the widely adopted Larson et al. \(\rho_\text{HI}/\rho_\text{H}2\) conversion factor, and that independently suggests that the inward moving molecular clouds must be in close proximity to the black hole. 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 grow as:

\[
M \approx 10^5 M_\odot \times \frac{r}{1 \text{kpc}} \times \left( \frac{N_H}{10^{22} \text{cm}^{-2}} \right)
\]

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^{23} cm\(^{-2}\) requires this distribution to be contained within a sphere of radius < 1 kpc, lest the limit set by 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 1.8 \times 10^8 M_\odot of cold gas present in the galaxy.

Codes, software, and data availability. Codes that we have written to both reduce and analyze the data presented in this Letter have been made publicly available at https://github.com/granttremblay/Tremblay_Nature_ALMA_Abell2597. Also available at https://casa.nrao.edu/. Plots were made using both Python’s MatPlotLib and Vizier, which is available at http://hgle.org/vizier/.