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GALAXY EVOLUTION

Thirsty galaxies thriving on gas streams

Young galaxies are most effective at converting gas into stars. Intense accretion of fuel is required to keep galaxies growing, but these gas streams have largely eluded observations. New instruments at optical telescopes are now uncovering clues of their existence.

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In the first two to three billion years of cosmic history, galaxies are observed to undergo a very intense phase of growth. During this epoch, hundreds of stars are born every year within a typical active galaxy, compared to the handful of stars that are born in star-forming galaxies today. Hydrogen, the raw fuel for star formation, must be rapidly accreted from the surrounding intergalactic medium to sustain this powerful activity over time. Yet, despite the expectation that streams of infalling gas are common around galaxies, direct observations of gas accretion have remained scarce. Establishing how galaxies get their gas remains an open challenge for observational astrophysics, with simulations offering most of the information on how gas accretion might occur. In this issue of Nature Astronomy, Christopher Martin and colleagues[1] provide additional clues to solve this conundrum. By using the Keck Cosmic Web Imager at the Keck Telescope, a new instrument designed precisely to image gas around galaxies, they have mapped in detail how hydrogen moves near two distant galaxies. With a novel modelling technique, these authors have uncovered new hints that the gas is moving towards the galaxies in flows that supply enough fuel to sustain the observed star formation activity.

Simulations[2,3] that describe the evolution of galaxies when the Universe was approximately two to three billion years old, the epoch in which galaxies were most active, generally predict that the intense formation of new stars is enabled by prominent gas accretion in the form of streams of hydrogen with temperatures below 10^5 K (Figure 1). In simulations, these "cold streams" or "cold flows" effectively deliver fuel to the central parts of star-forming galaxies with a rate that is sufficient to replenish the hydrogen tanks of galaxies, sustaining their activity for several billions of years. At redshifts above $z = 2$, most star-forming galaxies are expected to be fed by these cold streams, but, puzzlingly, astrophysicists have yet to obtain unambiguous empirical evidence of their existence. Observations are also needed to pin down the physical properties of these cold flows, which are not yet robustly predicted by simulations[4].

There are several reasons to explain the lack of direct detection of cold flows. Hydrogen inside the streams is diffuse and emits only a faint glow that has remained largely invisible even to the largest telescopes. Gaseous structures can still be probed in silhouette[5] as the light of a bright source, such as a background quasar or the galaxy itself, shines through it. However, these streams are expected to be thin and cast only modest shadows which, in most cases, cannot be attributed unambiguously to cold flows. As astrophysicists have focused their efforts on hunting cold gas accretion, tantalising candidates have accumulated in the literature[6,7], but a smoking gun has yet to be found.

For their observations, Martin et al. had an ace up their sleeve: the Keck Cosmic Web Imager[8] (KCWI) mounted at the Keck Telescope. Similar to the Multi Unit Spectroscopic Explorer[9] (MUSE) at the Very Large Telescope, KCWI is a new-generation integral field spectrograph (IFS) that enables observers to acquire images in which every pixel is a spectrum of the light recorded at that position. With an IFS, it becomes possible to detect much fainter emission from diffuse gas than with more traditional imaging techniques. Moreover, one can reconstruct a detailed view of the gas distribution and, simultaneously, of its motion. Leveraging this technological advancement, Martin et al. looked at two galaxies found at a redshift of $z=2.26$ and $z=2.61$, close to the peak of the star-formation activity of the Universe. These galaxies host two bright quasars, which provide an added boon for this experiment: as the light produced by these supermassive black-holes shines on the diffuse gas around the host galaxies, hydrogen is excited and emits characteristic radiation that is several times brighter than in typical galaxies.

With these new data, the authors reconstructed a detailed map of the extended disks of cold gas in the surroundings of these two galaxies, also gaining a high-definition view of the gas motion. By comparing to the data models for the gas motion with increasing complexity, including motion towards and around the galaxy while accounting for streams, they inferred that gas is moving towards the galaxy centres, thus uncovering a signature of cold gas accretion. The best model that describes these data further implies that the mass of hydrogen that is being accreted is comparable to, or even greater than, the mass converted into stars within these systems, which is in line with theoretical predictions and the required condition for star formation to proceed for billions of years. Moreover, these observations uncovered a characteristic pattern in the gas motion that is seen also in simulations of galaxies that are fed by cold flows. Quite tantalisingly, the direction through which the gas is being funnelled inward appears to align with elongations in the gas distribution, which are reminiscent of the end-point of cold streams seen in simulations.

While the link to cold flows remains still indirect in these observations, the work of Martin et al. offers a starting point for understanding better how galaxies get their gas. The current observations probe only gas in the immediate surroundings of galaxies and not the larger scales where the streams themselves would become visible, albeit at much lower brightness[10]. Future deeper observations may finally be able to uncover the telltale filamentary morphology of cold flows as seen in simulations, ideally extending this type of analysis to emission lines other than Lyα, which is affected by radiative transfer effects. Furthermore, this study relies only on a qualitative comparison between two galaxies and a single simulation, but as samples of extended gas disks around galaxies grow[11], techniques similar to those pioneered in this study can be applied to more systems to statistically detect the presence of cold flows. Finally, this study focuses on galaxies hosting quasars, which are easier to observe but potentially very different from typical star-forming galaxies. Extending this study to less remarkable objects will require a significant observational effort (hundreds of hours at large-aperture telescopes), but a worthy one to learn about the general galaxy population.

The era of IFSs at large-aperture telescopes has just begun and observational astrophysicists are already making great strides towards unveiling gas accretion. In the near future, very deep observations with KCWI and MUSE have the potential to uncover even more compelling pieces of evidence of the existence of cold flows. Moreover, with the next generation of 40-meter telescopes, currently under construction, it will be possible to routinely combine IFS observations of gas around galaxies in emission with spectroscopy in absorption against the galaxies themselves, enabling a more complete study of gas accretion. The smocking gun of the existence of cold streams has yet to be found, but astrophysicists are closing in.

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Figure 1 | **Map of the projected gas density, color-coded by temperature, of a simulated galaxy that is fed by cold-gas accretion at a redshift of z=3.** In this type of cosmological simulations, flows of gas with temperature below 10^5 K (shown in blue and purple) deliver hydrogen from the intergalactic medium to regions well within the virial radius (marked by a white dashed circle) of the central star-forming galaxy. The motion of this cold gas, as shown by projected velocity vectors, exhibits a complex pattern modulated by gravity and hydrodynamical effects, and includes a radial infall towards the galaxy.