FEATURE

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Research Area: Astronomy

The Life and Death of Galaxies

While they may seem almost simplistic, questions like "How do galaxies grow?" and "How do they die?" are not only fundamental but capture many of the most important current problems in the topic of galaxy formation. In seeking answers to these questions, astronomers hope to uncover the nature of physical mechanisms that drive the initial formation and evolutionary history of galaxies, including our own Milky Way.

While there are many promising paths for insights into these questions, I would like to address two new kinds of observational data sets that have great potential by offering unprecedented statistical power to analyses of the galaxy population.

The first is a technological breakthrough that brings a 50-fold increase in our ability to collect *spatially-resolved* spectroscopic observations. Imagine the equivalent of a medical CAT scan for a galaxy — a 3D "datacube" describing the spectrum at every location, with the power to decompose the galaxy into its primary constituents, stars and gas, and to reveal the detailed nature of those constituents. Now imagine obtaining these galaxy "CAT scans" for thousands of nearby galaxies. The ongoing MaNGA Survey (Mapping Nearby Galaxies at Apache Point Observatory), of which I am the Principal Investigator, aims to eventually cover 10,000 galaxies by the time it finishes in 2020, but even today, it is the largest survey of this kind. This rich data set is helping us catch evolutionary mechanisms "in the act," including our 2016 discovery of an entirely new class of galaxy that we call "red geysers" which offer a valuable clue to the mystery of how dead galaxies stay dead.

The second advance is deep imaging across very large portions of the sky, exemplified by surveys like the Subaru Telescope's Hyper Suprime-Cam, also led here at the Kavli IPMU. These imaging surveys will catalog huge numbers of galaxies (tens of millions) over a vast range in cosmic time. For the first time, it will be possible to chart the evolving galaxy population over the last 6-8 billion years with high precision, illuminating patterns of growth and pathways of evolution that will constrain the underlying physical processes that drive them.

Understanding Galaxy Death with MaNGA

For most of their lives, galaxies are lush environments for turning gas into stars. Until suddenly, they aren't. Over the last few billion years, a mysterious kind of "galactic warming" has turned huge numbers of galaxies into deserts devoid of fresh young stars. It seems we are living through an era marked by the "death" of star formation in galaxies. Our Milky Way, itself, is heading down the path toward extinction (but not to worry, it still has a couple billion years to go!). The puzzle has been figuring out what keeps the gas in these dormant galaxies too hot and energetic to form stars.

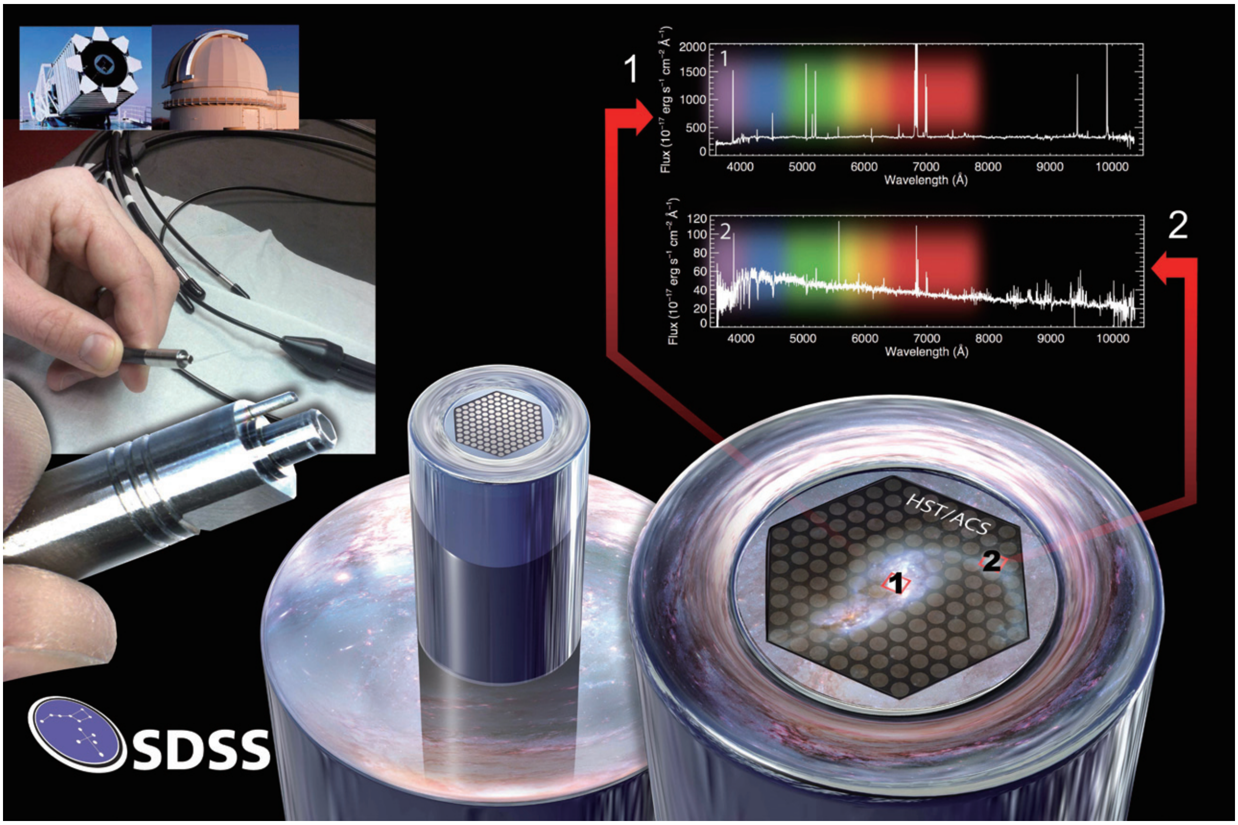

Figure 1. Illustration of MaNGA's fiber-bundle technology. Using a tightly packed hexagonal array of optical fibers, spectroscopic measurements can be obtained across the full face of target galaxies. For a given pointing on the sky, MaNGA deploys 17 such fiber-bundles which are positioned on targets by plugging them into a custom-drilled aluminum plate. (Credit: SDSS)

One problem in solving this mystery has been that current galaxy surveys are too small to overcome statistical uncertainties and establish definitive links between evolving populations. The evolving density of any population has never been measured to better than 20-30% and the situation worsens at high masses where samples are more complete but galaxies are increasingly rare. For the first time, wide-field surveys like the HSC Survey (see below) will make it possible to equate the diminishing numbers of one population (e.g., star-forming galaxies) with the rising occurrence of another (e.g., dormant disk galaxies). Establishing the pathways that lead to galaxy death will help us test global predictions of the various mechanisms involved.

But to fully diagnose what ails dying galaxies, we must peer inside them and study their inner workings. This is one of several motivations for the MaNGA Survey, a core program in the current-generation Sloan Digital Sky Survey-IV (SDSS-IV) that began in 2014 and will complete observations in 2020. As shown in Figure 1, MaNGA works by bundling together sets of optical fibers into tightly-packed arrays, enabling spectral measurements across the face of each of ~10,000 nearby galaxies. Because the life story of a galaxy is encoded in its internal structure—a bit like the way the life story of a tree is encoded in its rings — MaNGA is allowing us to map out the distribution of the fundamental galactic building blocks: the dark matter whose gravity binds the galaxy, the gas from which stars form, the stars themselves, and the chemical elements that these stars produce in their nuclear furnaces and then return to the galaxy during their explosive deaths. We are mapping out both the history of the formation of stars and the motions of the stars and gas at each location in the galaxy.

The Mysterious “Red Geysers”

With the first year of MaNGA galaxy observations in hand, Edmond Cheung, a Kavli IPMU postdoctoral fellow, and I began poring over the maps of quiescent, so-called “red and dead” galaxies in the sample, a population devoid of star formation that accounts for roughly 30-40% of the galaxies MaNGA is targeting.

In recent years, it had become clear that quiescent galaxies often contain ionized gas, so the question was what prevents this gas from eventually cooling and condensing to form new stars. And with plenty of fresh gas in the universe trickling into galaxies all the time, one would expect “rejuvenation” of star formation to be more common. Even a smattering of new star formation would be apparent in these galaxies because fresh young stars are so much hotter (and bluer in color) than their elderly counterparts. Instead, once extinguished, star formation seldom appears to return.

The MaNGA maps confirmed the widespread presence of ionized gas in red and dead galaxies, but an intriguing spatial pattern caught Edmond’s attention. Soon, we began to notice this pattern appearing in quite a few examples. It looked like irregular, bisymmetric streams of gas, outflowing from the central galaxy nucleus. Intrigued but skeptical, we named these objects “red geysers.” Red because they lived in non-star-forming galaxies, characterized by red colors, and “geysers” because they looked like outflows of material.

For over a decade, it has been realized that one way to solve the mystery of galaxy death was to invoke the potential power of a central supermassive black hole. If the energy liberated from even small amounts of material encircling such a black hole could somehow be injected into the galaxy’s ambient gas, distributed over much larger scales, this could be the heating source needed to keep hot gas from cooling and forming stars. The question was whether such a mechanism existed. Edmond and I wondered if red geysers held the answer.

With a sample of 8-10 red geysers to study, we chose to focus on a galaxy we nicknamed, Akira, after the famous Japanese manga character (an homage to our home institution in Japan and to the inspiration for the name of the MaNGA survey). In the previous color imaging, Akira appears to be a typical and unremarkable elliptical galaxy with no ongoing star formation. It is interacting, however, with a much smaller star-forming companion (we named this galaxy Tetsuo), as evidenced by long tidal tails that emanate from Tetsuo and connect the two galaxies (Figure 2).

The MaNGA data, however, reveal Akira to be

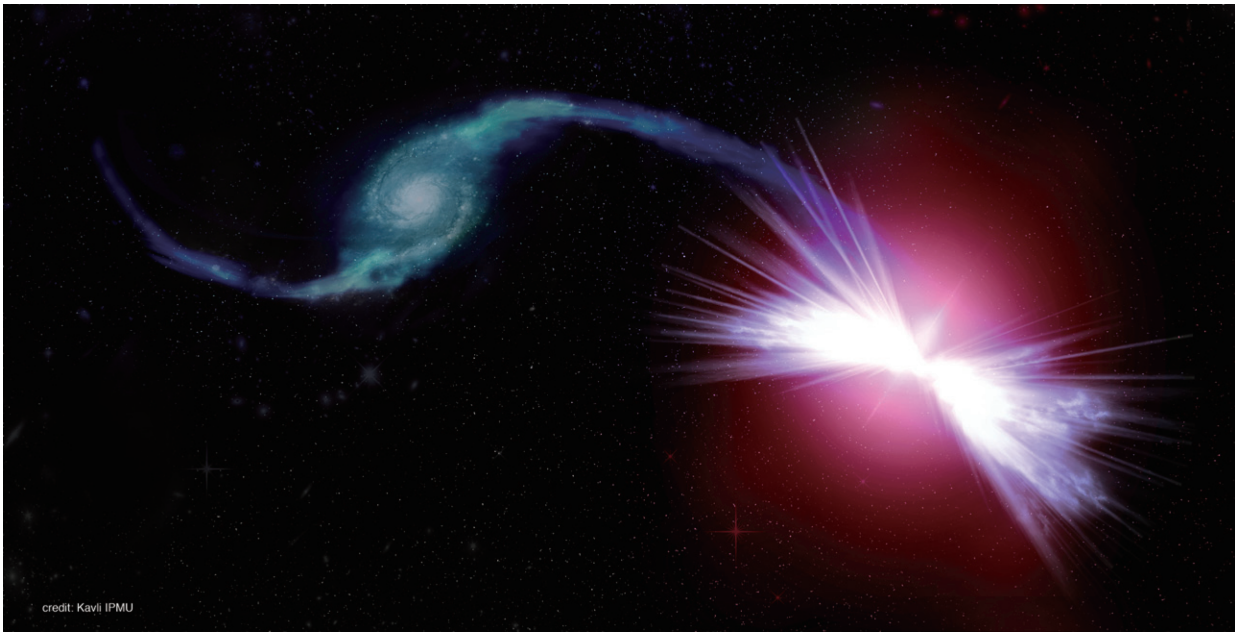

Figure 2. An artist's impression of the prototypical "red geyser" Akira (right) and its companion Tetsuo (left) in action. Akira's gravity pulls Tetsuo's gas into its central supermassive black hole, fueling winds that have the power to heat Akira's gas. The action of the black hole winds prevents a new cycle of star formation in Akira. (Credit: Kavli IPMU)

much more active and interesting than it would appear on first glance. The ionized gas map exhibits the tell-tale outflow-like pattern, but by studying the motion of this gas we proved that it was entirely decoupled from the motions of stars and, furthermore, that the gas was moving at sufficient speeds that much of it was likely to escape the confines of its host galaxy. These arguments demonstrate that Akira and red geysers in general harbor winds, likely driven by central supermassive black holes.

Other kinds of MaNGA maps reveal a second component of much colder gas in Akira that we believe was accreted from the smaller, star-forming companion. We performed some simple calculations to demonstrate that this gas should be cooling and forming stars at a rate that is not detected. What is more, the heating power of the red geyser wind appears sufficient to balance the cooling rate. We therefore argue that red geysers represent an important process in action: the triggering of a black hole wind that deposits heat into the surrounding gas and thereby keeps dead galaxies from rejuvenating and forming new stars.

In May 2016, our work on this exciting discovery was published in the journal *Nature* (Cheung et al. 2016, *Nature*, **533**, 504). Following press releases by the Kavli IPMU and SDSS, more than 100 articles appeared in news outlets around the world including the *PBS NewsHour* website and *The Asahi Shimbun* (朝日新聞).

How Do Galaxies Grow?

Turning from death to growth, a fundamental prediction of our standard cosmological framework is that structures in the universe grow "hierarchically." While galaxies represent incredibly massive structures — our Milky Way has the mass equivalent to 10^{11} Suns — they are a factor of 30 or more smaller compared to the amount of mysterious dark matter that envelopes them in a gravitationally bound system that we call a dark matter halo. From the cosmological standpoint, the growth of structure is therefore dominated by dark matter, and so a simple way to express hierarchical growth is to say that, at any given time, the largest dark matter halos are the most recent ones to form and do so through the merging of smaller halos. The question is whether galaxies follow this pattern as well.

Naively, we would expect the answer to be yes. After all, galaxies, residing at the centers of their dark matter halos, are largely pulled around by the dark matter. If halos merge, galaxies should merge. And if we can approximate the galaxy's total mass from the amount of light it emits, we would expect distributions of the stellar mass, M_*, in galaxies to evolve hierarchically. The most massive galaxies today should have assembled their stars recently.

Strangely, some recent studies have claimed the *opposite* trend, finding that massive galaxies were first assembled long ago while the number of low-mass galaxies increases with time. Because a concordance of observational constraints has confirmed hierarchical models of the cosmic growth of structure, it appears we do not understand how galaxies grow inside their dark matter halos.

This confusion points to a major challenge: We currently lack definitive measures of galaxy growth rates, especially in the last half of cosmic history. The problem is that previous galaxy samples have been built from surveys of only 0.01% of the sky, the equivalent area of about 10 full moons. While they reach great distances, these "pencil beam" surveys are too small to provide adequate statistics. As they pierce the "cosmic web" and intersect overdensities and voids, the statistical properties of the recovered samples bounce around, painting an uncertain picture about the true, underlying distribution of galaxy properties.

A Powerful Role for the Subaru Telescope

In the coming years, new, panoramic wide-field surveys will for the first time sample the cosmic volumes necessary to measure galaxy growth, ushering in a new era of high-precision galaxy evolution studies. In the longer term, facilities like Euclid and LSST will provide unprecedented statistical power. But, major advances are possible sooner with instruments like Hyper Suprime-Cam (HSC), which is carrying out an unprecedented imaging survey. The "Wide-layer" component of this survey reaches image depths capable of detecting galaxies when the universe was less than half its current age. But instead of covering an area of only a few square degrees as in past surveys, HSC-Wide will span 1400 deg^2, the equivalent area of 5600 full moons tiled across the sky!

Having started in 2014, the HSC survey is 10-20% complete and yet, we are already learning that addressing the question of galaxy growth

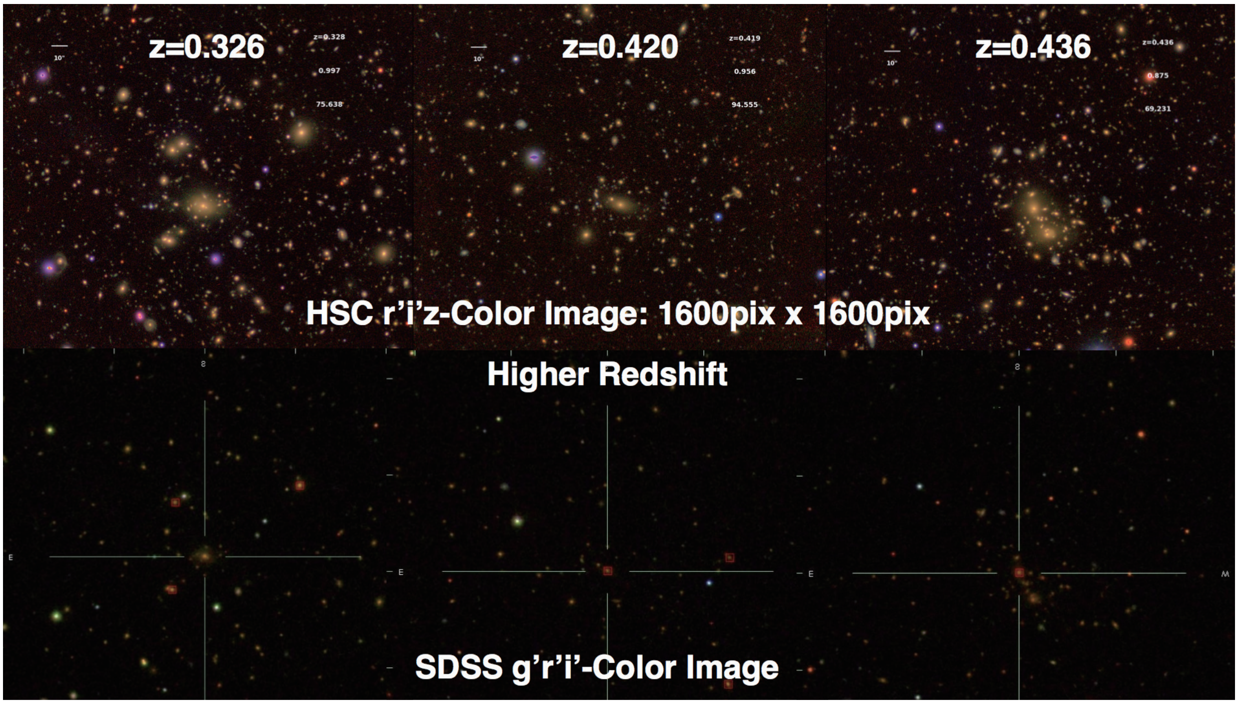

Figure 3. A comparison of deep HSC images (top row) to shallower Sloan Digital Sky Survey images (bottom row) for three massive galaxies at redshifts (z) of 0.3-0.4 (roughly 3-4 billion years ago). The greater image depth of HSC captures more features, including the fuzzy outskirts of massive galaxies, which may account for much of the mass. (Credit: Song Huang)

requires not only the power of large statistically representative volumes, but also imaging depths that are sensitive to the outer regions of massive galaxies. The comparison between HSC images and the previous, shallower images from the Sloan Digital Sky Survey (SDSS) reveal this clearly in Figure 3.

While the fuzzy outskirts of massive galaxies may be intrinsically faint, they extend far beyond the central confines of the galaxy and, when added up, contain a significant number of stars and mass. Thus the lack of galaxy growth observed in previous, much smaller surveys may also owe to the fact that we have *missed* the outskirts, where this growth may occur.

In the near future, HSC is poised for a breakthrough in this topic. First, it will be possible to revisit previous measurements of the stellar mass of galaxies. In many cases, these estimates will be revised upwards thanks to HSC's ability to measure stars in the outskirts. Second, as the survey matures, we will soon have the samples needed to address previous statistical limitations and chart the rate of growth at high precision. On the question of whether galaxies grow hierarchically, the jury is still out. But with HSC making sure-footed progress, stay tuned to find out!