FEATURE

Kavli IPMU Associate Professor John Silverman
Research Area: Astronomy

Cosmic Fireworks‘花火’in Colliding Galaxies

For much of their history, galaxies grow by forming new stars out of their gas reservoirs at a steady pace over billions of years. On occasion, an episode of intense star formation occurs, namely a ‘starburst’, that is usually the result of a collision between two massive galaxies (Figure 1) with an eventual merger in many cases. These spectacular events are relatively short-lived (~100 million years), somewhat analogous to the fleeting 桜‘Cherry blossom’season in Japan. In addition to generating new stars, galaxy mergers are effective at channeling gas to their centers to grow a supermassive black hole and a central concentration of stars (namely a bulge) that is a ubiquitous feature of massive galaxies in the nearby Universe.

Astrophysicists, both theorists and observers, view starbursts as an important laboratory to study the more extreme physical conditions (i.e., density, temperature and pressure) of the cool gas component of the interstellar medium. To understand why certain galaxies form stars at different rates, it is important to measure the properties of the molecular gas out of which stars form and over a range of scales from giant molecular clouds within galaxies to galaxy-wide quantities.

In the nearby Universe (out to a distance of ~ 50 Megaparsecs or 163 million light years), we have a clear understanding of the impact of galaxy interactions and mergers on the rate at which galaxies form their stars. In the more distant and younger Universe, the situation may not be the same since galaxies are richer in molecular gas and hence may be able to form stars rapidly without any help from a merger. Until recently, it has been challenging to study the molecular gas properties of galaxies at great distances.

A new window on distant starburst galaxies with ALMA

The Atacama Large Millimeter/submillimeter Array (ALMA), a telescope located in Chile on the Chajnantor plateau, is now enabling investigations of the molecular gas (and dust) properties of galaxies out to the largest distances and on smaller physical scales than previously possible. This is due to the large collecting area of 66 antennas that work in unison, as an interferometer, and can be spread over wide separations that reach up to 16 kilometers (Figure 2) thus providing the highest resolution images possible over a wavelength (frequency) range of 9.6 to 0.3 millimeters (31 to

Figure 1: Hubble Space Telescope image of the interacting galaxy pair, Arp 87 (courtesy STSCI).

1000 GHz).

ALMA is an international observatory with Japan contributing as a major partner including Taiwan and South Korea that together constitute the East Asian participation group. In Japan, ALMA offers remarkable capabilities to fully explore interesting objects, such as distant quasars and galaxies that reside in the first emerging large-scale structures, currently being discovered by the wide and deep surveys with Subaru Telescope.

With respect to distant starburst galaxies, past interferometric investigations were restricted to the most luminous examples at the expense of having limited spatial information. With ALMA, we can now study the spatial and velocity distribution of gas within distant galaxies with ease.

Finding bona-fide distant starbursts

To know exactly where in the sky to point ALMA, we need to identify which galaxies are undergoing a starburst phase. Such an effort requires a multi-wavelength observational approach to make key measurements that shed light on their current state and history of formation. With limited observational resources and manpower to compile such observational data sets, multi-national collaborations have been effectively pooling resources for such purpose. Here, we describe our own effort in the COSMOS field, a contiguous region of the sky, about nine times the size of the moon, that has been surveyed by numerous telescopes on the ground (e.g., VLT, Subaru, and Keck) and in space (e.g., *Hubble*, *Spitzer*, and *Herschel* Space Telescopes) that cover most of the electromagnetic spectrum. Japan is an important participant in the COSMOS survey and is now leading in the next generation of wide-field optical surveys with Subaru including the imager Hyper Suprime Cam and Prime-Focus Spectrograph to follow in a few years.

As a first step, we need to assess the rate at which new stars are being formed, usually in terms of the mass in stars per year. Since stars are born in regions of dense molecular gas, they are enshrouded by dust thus making it difficult for optical or ultraviolet emission to escape without being absorbed and reradiated at longer wavelengths. To account for dust-obscured star formation, the brightness of a galaxy at infrared wavelengths is used as a measure of the rate that stars are being produced. Due to warm thermal 'infrared' emission from the Earth, space-based telescopes (i.e., *Spitzer*, Akari, and *Herschel*) are required for their detection at wavelengths greater than a few microns. Over the last decade or more, we have learned that the rates that galaxies form new stars can be off by an order-of-magnitude, if restricted to optical observations alone, especially in the case of starburst galaxies.

To measure the intrinsic star formation rate, we need to know the distance to the galaxy since the detector on *Herschel* or *Spitzer* only provides a brightness for distant galaxies, not its intrinsic luminosity. Furthermore, an accurate measure of the distance is needed to tune ALMA to the appropriate frequency. This requires observations with a spectrograph to disperse the optical or near-infrared light to detect spectral features that provide a measure of a galaxy's redshift, a consequence of the expansion of the Universe, that is directly related to its distance given our current cosmological model.

In our case, we spent 60 nights at Subaru Telescope observing over 3500 star-forming galaxies with the Fiber Multi-Object Spectrograph (FMOS). As a result, we identified close to 1500 galaxies with a detection of emission lines such as Hα from ionized hydrogen gas that provided a measure of their redshift between 1.4 and 1.7. This project was a collaboration between researchers in Japan, Europe, and the United States. For some perspective on future technological advancement, the same effort could be accomplished with only a few nights using Subaru's Prime-Focus Spectrograph. Even so, we identified 150 galaxies (from the 1500 with redshift measurements) detected at far-infrared wavelengths with the *Herschel* Space Observatory. Therefore, we are able to estimate their star formation rate and single out the starburst galaxies that are forming stars at remarkable rates, well above the typical population.

Observing molecular gas as traced by carbon monoxide

Armed with a sample of bona-fide starburst galaxies at high redshift, we can now observe with ALMA at the appropriate frequency to detect an emission feature given off from regions of

Figure 2: Atacama Large Millimeter/submillimeter Array (ALMA; credit: ESO).

molecular gas where stars are forming. Traditionally, carbon monoxide (CO) has been used as a tracer of the total molecular gas content of galaxies that is primarily composed of molecular hydrogen (H_2). Emission from a CO molecule is emitted during transitions from a higher to a lower rotational state, initially excited due to collisions with H_2 molecules. The level of excitation is indicative of the presence of gas at different temperatures and densities. With the spatial resolution of a telescope dependent on the wavelength (or frequency) of light, higher order transitions can produce maps of the gas distribution at greater spatial resolution due to their higher observed frequencies. The aim here is to measure the total CO luminosity with ALMA of a given molecular transition (e.g., J = 2 to 1; rest frequency = 230.54 Gigahertz) and convert the luminosity to the mass in molecular gas. The relation between CO luminosity and gas mass has been calibrated based on molecular clouds in our Milky Way and galaxies both at low and high redshift. The latter require a measure of the gas mass in galaxies, independent of CO luminosity. There is considerable ongoing debate about the accuracy of such relations including that for starbursts that may differ substantially from more typical star-forming galaxies.

A quintessential starburst event induced by a collision of two galaxies at high-*z*

At Kavli IPMU, we have been using ALMA to detect the total CO(2-1) emission from 12 starburst galaxies at redshifts $z \sim 1.6$ (an epoch when the Universe was 30% of its current age), selected as having star formation rates ≥ 4 times higher than more typical galaxies. Their star formation rates

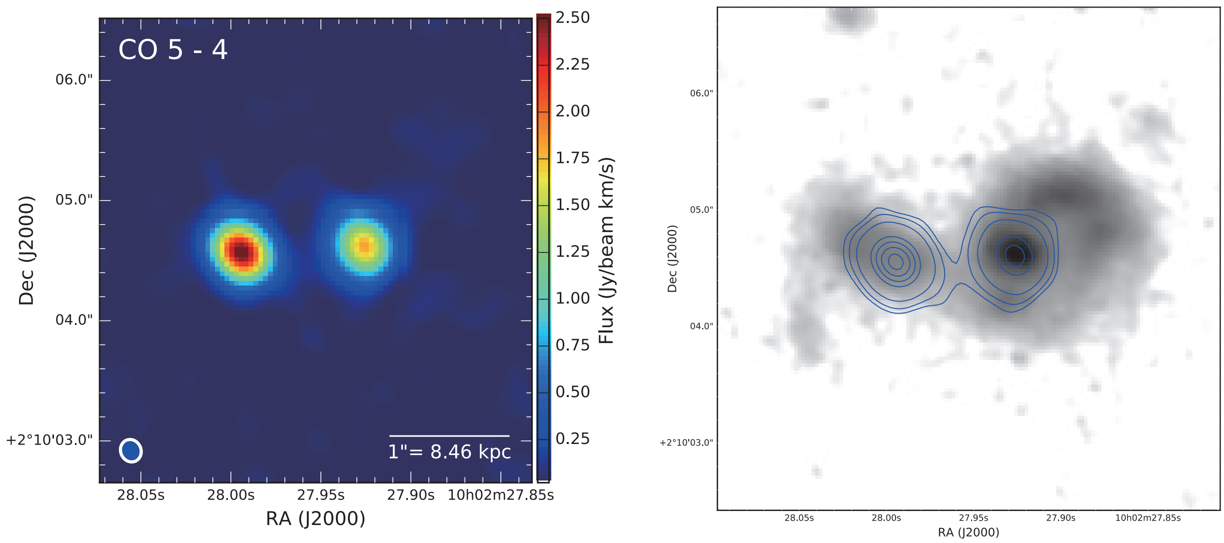

Figure 3: *Left* - ALMA map of CO(5-4) emission from two galaxies in PACS-787. *Right* – An infrared image taken with the Hubble Space Telescope using the Wide-Field Camera 3 with CO indicated by the blue contours.

range from ~100 to 700 solar masses per year. CO emission is clearly detected in all but one that indicates the presence of abundant gas reservoirs in these starburst galaxies.

Unsurprisingly, the brightest galaxy in CO is the galaxy (PACS-787) with the highest level of star formation at 720 solar masses per year. We were curious as to what factors could contribute to a galaxy having such a high star formation rate when simulations of gas-rich galaxies in mergers, similar to those in the high redshift Universe, typically produce only modest enhancements in star formation, not enough to reproduce the rates seen in PACS-787.

To answer this question, we re-observed PACS-787 at a higher resolution by detecting the CO(5-4) emission line at a rest frequency of 576.27 Gigahertz (Figure 3 left panel). To our astonishment, the CO emission was now resolved into two distinct galaxies with a separation between the galaxies being 8.6 kiloparsecs. With such a high star formation rate, we expected the galaxies to be close to final coalescence as seen in simulations, but instead the two galaxies are still in the initial stages of an interaction. With a recent infrared image of PACS-787 taken with the *Hubble* Space Telescope (Figure 3 right panel), we now see clear evidence for an ongoing collision between the two galaxies since there are signs that some stars have been tidally stripped and form a bridge between the two galaxies that is also evident in CO emission.

Based on these observations, we conclude that the high star-formation rates in PACS-787 are based on a set of optimal factors including the interaction of two gas-rich galaxies and an orbital configuration conducive to drive gas to the nuclear regions thus powering a central starburst in each galaxy. We further find that the CO emission in each galaxy is rotating as a disk that provides further diagnostics on the amount of molecular gas present, independent of the CO luminosity.

A fuel-efficient engine in distant starbursts

There is much interest in determining if the star

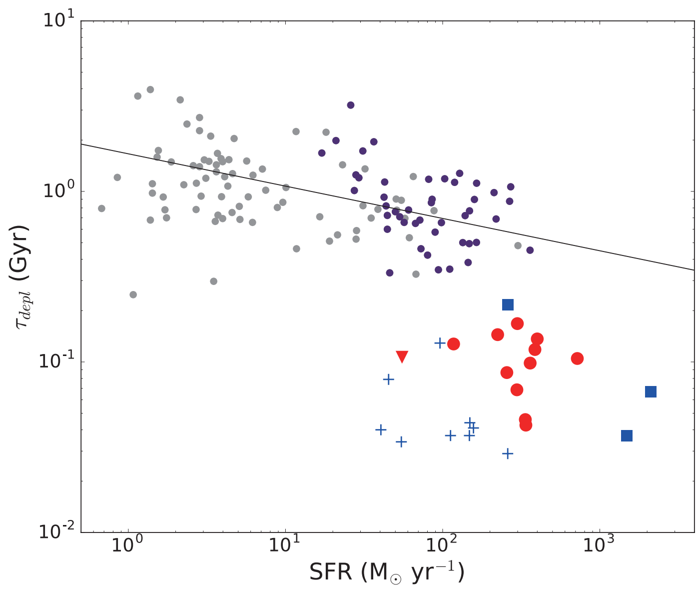

Figure 4: Time ($t_{depl} = M_{gas}$ / SFR) to deplete the full gas reservoir of a galaxy at a given star formation rate (SFR). Starburst galaxies are shown as large colored symbols including our ALMA sample in red. More typical star-forming galaxies are indicated by smaller circles and a best-fit linear relation.

formation rates in distant starbursts are due to an elevated gas mass, a more efficient conversion of gas to stars, or a combination of the two. To distinguish between these scenarios, we convert the CO luminosity to molecular gas mass for all twelve starbursts in our sample using the appropriate relation. Regarding the efficiency, we measure a time scale for a galaxy to consume all of its gas by dividing the gas mass by the star formation rate. A galaxy that is efficiently forming stars will have a short gas depletion time.

As shown in Figure 4, the depletion times for our starbursts are between 50 – 150 million years, substantially shorter than more typical star-forming galaxies with depletion times around 1 billion years. This difference in times scales to form stars indicates that starbursts are likely triggered by a mechanism (e.g., galaxy merger) that induces conditions more favorable for star formation to proceed at such high rates. The debate is not completely settled since there is remaining uncertainty on the appropriate value of the factor to convert CO luminosity to gas mass for high-*z* starbursts (and more typical galaxies).

Further progress with ALMA will be afforded by higher resolution observations to determine the physical characteristics of star-forming regions within galaxies down to ~100 parsec resolution. With new samples of high redshift galaxies to come from Subaru surveys, our understanding of star formation will vastly improve over the years to come.