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Cosmic Collisions in the Distant Universe

The Near-Infrared Integral Field Spectrometer (NIFS) on Gemini North is a powerful instrument for exploring the gas morphology and dynamics of galaxies in the far-distant universe. Recent observations of submillimeter galaxies with NIFS by the author have led to a better understanding of the origin of intense star formation occurring within these galaxies. The kinematic properties recorded by NIFS suggest that these systems are actually made up of galaxy mergers and that these interactions potentially provide the trigger for rapid star formation.

Some of the most extreme star formation in the universe occurred three billion years after the Big Bang, in a population of galaxies enshrouded in dust. The high energy (short wavelength) radiation emitted from the young massive stars in these systems was reprocessed by the dust and emitted at far-infrared wavelengths. Since the radiation we observe from these galaxies was emitted 10 billion years ago, and since the universe is expanding, we see that light redshifted to longer submillimeter wavelengths, giving rise to their name: Sub-Millimeter Galaxies (SMGs).

The advent of the Submillimeter Common-User Bolometer Array (SCUBA) on the James Clerk Maxwell Telescope (JCMT) in Hawai'i first enabled astronomers to detect these high-redshift systems. Follow-up observations of this population revealed the SMGs to have extremely high far-infrared luminosities, classing them as Ultra-Luminous InfraRed Galaxies (ULIRGs). Astronomers have also studied ULIRGs in the local universe, finding they are often compact objects. The SMGs, however, appear extended, which suggests they are not simply higher redshift versions of the local ULIRGs.

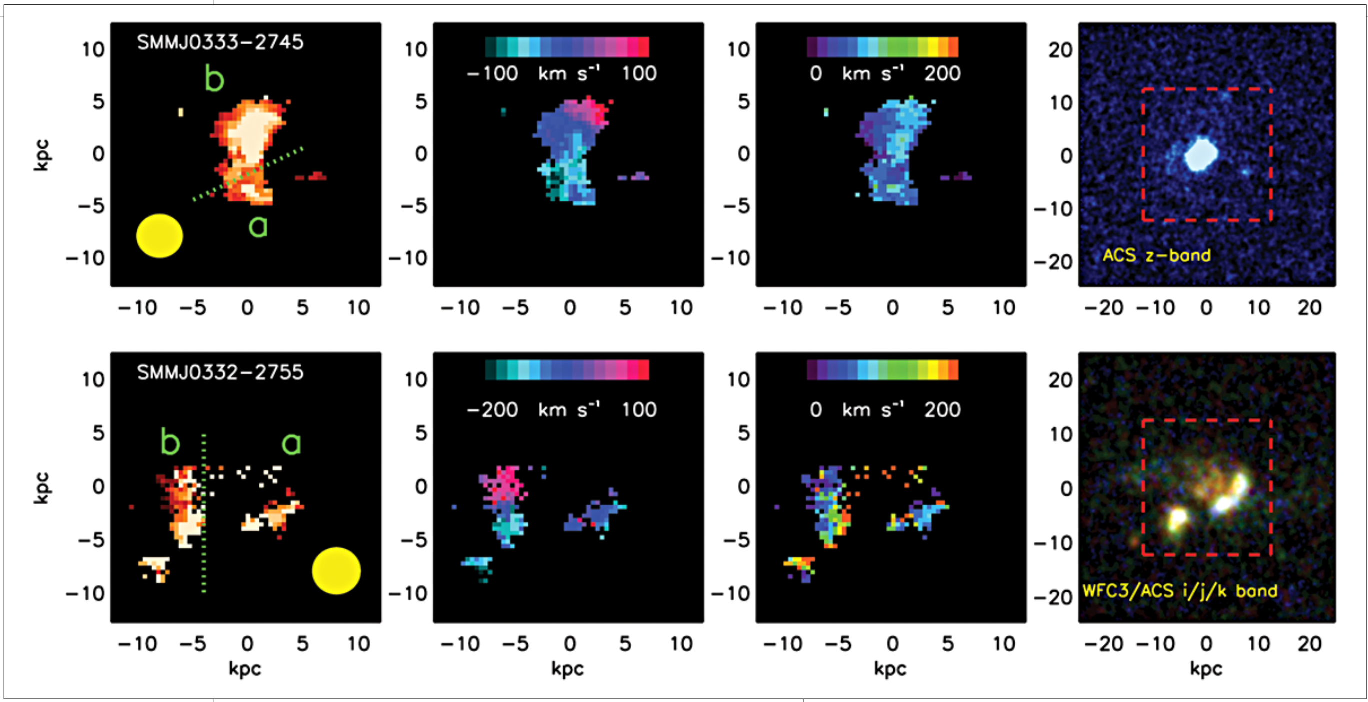


Figure 1.

The Hα intensity, velocity, and velocity dispersion maps of two of the SMGs observed with NIFS. We show HST imaging also. All the SMG systems observed show disturbed dynamics and multiple peaks of star formation intensity.

Triggering the Rapid Star Formation

SMGs have large reservoirs of molecular gas that provide the fuel for rapid star formation. Indeed, SMGs can grow quickly, creating a massive galaxy in only 100 million years. SMGs therefore represent an immensely active phase in galaxy evolution and are thought to be the progenitors of the massive elliptical galaxies observed in the local universe.

After 15 years of intense study, our detailed understanding of SMGs is still limited to only a handful of objects with spatially resolved images and spectra. In particular, we still don't fully understand what triggers the extreme star formation in SMGs. Galaxy simulations predict that two galaxies merging could cause an ultra-luminous burst, as observed in SMGs. To test this hypothesis, we need to observe the dynamics and morphologies of the gas within the SMGs, hunting for the signatures of multiple colliding components.

Tracing the gas dynamics within high-redshift systems has only been made possible in recent years with the development of Integral Field Units (IFUs), such as the Near-Infrared Integral Field Spectrometer (NIFS) on Gemini North and the Spectrograph for INtegral Field Observations in the Near Infrared (SINFONI) on the Very Large Telescope (VLT). These units enable us to trace the emission lines across the galaxies. The gas dynamics can then be spatially resolved by tracing the shape and position of emission lines detected.

Tracing the Star Forming Gas

The hydrogen-alpha (Hα) spectral line is emitted from regions where hydrogen is ionized by hot young stars and therefore traces the star-forming gas. We mapped this emission line within five SMGs using NIFS and also three SMGs using SINFON to gain spatially resolved information about the intensity of star formation and the velocity and dispersion of the gas. The intensities of the Hα line map the star formation distribution across the galaxy; the position of the line (in wavelength) gives the velocity map of the gas, and the width of the line gives the velocity dispersion map of the gas.

We established that the gas within SMGs is disturbed and turbulent, often tracing multiple interacting components (Figure 1). There are no clear rotation curves in these systems, which one would expect if they had disks. This provides strong evidence that SMGs are merger systems and the merging process could trigger the intense star formation.

Quantifying a Merger

To find out how symmetrical SMGs are, we run a "kinemetry" analysis, fitting ellipses to the velocity and dispersion fields. The ellipses are fit at increasing radii, and the properties of the best-fitting ones at each radius are used to establish the level of asymmetry.

Figure 2 shows the results of running this analysis on the SMG sample and also other galaxies. The SMGs have higher values of asymmetry in both the velocity and dispersion fields than the more "normal" star forming galaxies of the SINS (Spectroscopic Imaging survey in the Near-infrared with SINFONI) sample and also the sample of low redshift spiral galaxies from the SINGS (Spitzer Infrared Nearby Galaxies Survey) sample. This suggests that SMGs have distinct dynamical properties to other populations of star forming galaxies.

The background red-blue pixels in Figure 2 represent the results of running the kinemetry analysis on template disks and mergers. The dotted line marks the division between the two populations. We find that all the SMGs lie in the red "merger" region of the plot. This provides further considerable evidence that the SMGs are merger systems.

What Types of Systems are Merging?

After establishing that the SMGs are mergers, we then hunted for their components in the star formation distributions. First, we matched the SMG systems to any components observed in the available imaging, or divided them by the contours of the minimum star formation intensities, so that the peaks in star formation lie in separate components. The division is shown by the green dotted lines in Figure 1.

We note, however, that splitting the sources into components does not necessarily represent the two distinct merging objects, since these systems could have evolved to the point where the gas and stars of the component systems have already started to mix. However, this separation offers a starting point to establish the types of systems that might have merged and triggered the extreme star formation phase in the SMGs.

We find that the components often have similar properties to the sample of star forming galaxies found at the same redshift as the SMGs but with more moderate star formation rates; the SINS sample of galaxies. This implies that two moderately star-forming, disk-like, galaxies could merge together causing this burst in extreme star formation.

SMGs in Massive Halos

The offsets in position and velocity between the components within the merging systems can be used to constrain the average halo mass of SMGs. We achieve this by com-

Figure 2.
The asymmetry measures of the velocity and dispersion fields for the sample of SMGs compared to a number of other galaxies (low-redshift ULIRGs and other star-forming galaxies). All of the SMGs lie in the merger region (red background) classifying all of the SMGs as mergers.

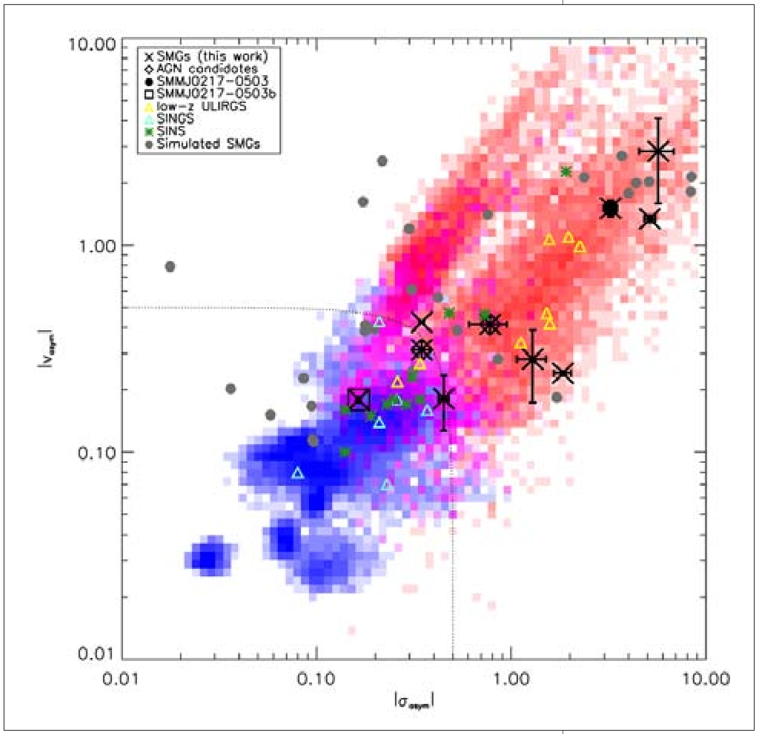
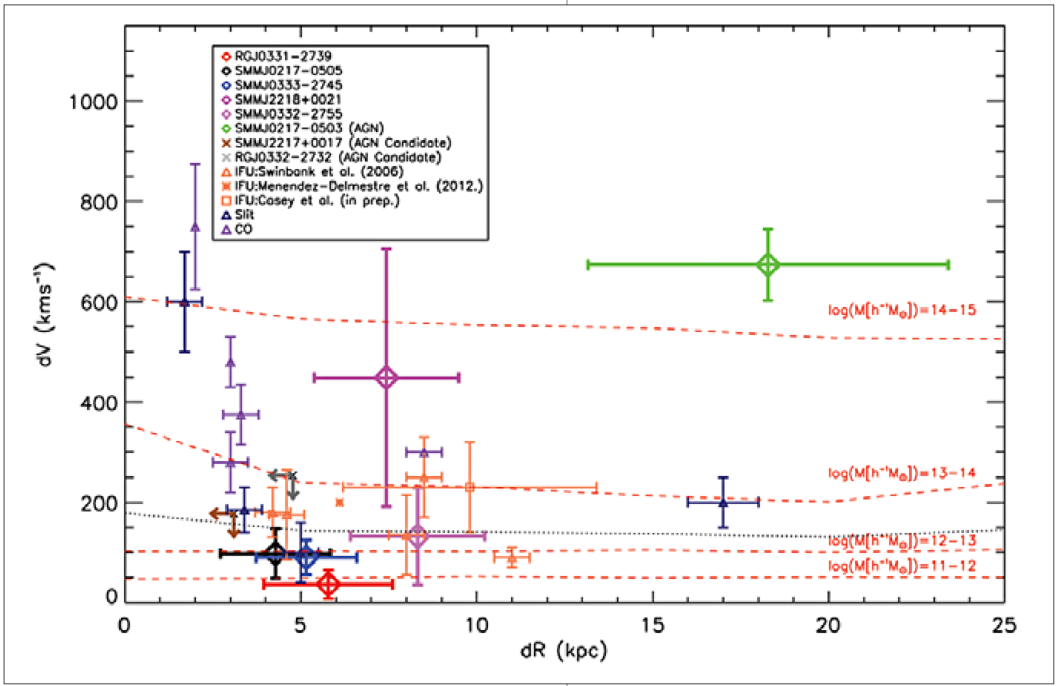


Figure 3. *The position and velocity offsets between the merging components observed in the SMGs compared to the offsets within galaxy halos of varying mass ranges extracted from the Millennium Simulation database (orange dashed lines). The SMG offsets are best described by the halo masses between 10^{13} and 10^{14} solar masses.*



paring the observations to the properties of simulated galaxy halos extracted from the Millennium Simulation database. Within each halo we identify the constituent subhalos, then measure the average offset between the most bound subhalo and the other subhalos. We therefore derive spatial and velocity offsets for simulated galaxy halos in various mass ranges. Figure 3 compares our observed offsets to the simulated ones and shows that the SMG offsets are best described by the simulated galaxy halo masses between 10^{13} and 10^{14} solar masses, which is more massive than previous measures of SMG halo masses.

The Future

The arrival of telescopes capable of millimeter interferometry has enabled the study of the fuel for rapid star formation in early galaxies. It also allows us to trace their molecular gas in the same detail as their ionized gas. By combining these observations, it will be possible, to probe the complicated gas processes in great detail. We can then better constrain the progenitor systems of the mergers, understand the triggering process of the prodigious star formation, and also explore the evolution of these systems towards the massive elliptical galaxies observed in the local universe.

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