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A Tiny Galaxy Blows Big Bubbles

A key ingredient in contemporary galaxy evolution models are feedback processes. By this terminology we encapsulate astrophysical phenomena that inject significant amounts of energy and momentum into a galaxy's interstellar medium. In some cases, feedback may have relatively modest effects, but in others it may be dramatic and transformative. The latter is thought to occur frequently in small and lightweight actively star-forming "dwarf" galaxies (star-burst galaxies). Active star-formation connotes that the galaxy gives birth to very massive (i.e., up to 100 times the solar mass, or more) and short-lived stars. After three to five million years, the cores of these stars collapse and giant nuclear explosions, dubbed supernovae, blast vast amounts of material into the surrounding space. The energy and momentum injected by supernovae into the interstellar gas may accelerate matter to such high velocities that it may potentially escape from the low-mass dwarfs, as their gravitational attraction is not very strong. Therefore, little to no gas might be available to fuel the formation of the next generation of stars. This quenching of star formation in low-mass galaxies due to feedback is, in fact, a crucial requirement for successful models of galaxy evolution in the Universe. Models without quenching predict an excessive number of star-forming dwarf galaxies — in disagreement with observed galaxy counts. Moreover, feedback from small galaxies also impacts the intergalactic medium, i.e., the space between galaxies. The latter is particularly relevant for the phase transition from a neutral to an ionised Universe during the so-called "Epoch of Reionisation" that lasted from about 500 million to 1 billion years after the Big Bang. To truly understand quenching and the "Epoch of Reionisation", we require an accurate quantitative understanding of feedback.

Developing ab initio physical models that quantitatively describe feedback is a complex task. For this, we must deal with involved physical processes (e.g., radiation-hydrodynamics). We also have to account for many (known) unknowns regarding the galactic environments in which these physical processes occur (e.g., the density and temperature distribution of the interstellar and circumgalactic gas). Such models are needed to better understand what feedback can and cannot do to a galaxy. For example, we aim to quantify the strength of feedback-driven galactic winds and the amount of matter that may actually escape from the galaxy's gravitational potential well harbouring the galaxy. Empirical insights from observations may nourish our quantitative understanding in this respect. In turn, this will help to constrain astrophysical and cosmological models.

Making direct images of the very faint and diffuse gas expelled from galaxies is, however, very challenging. Feedback-driven ejecta may emit, under certain conditions, emission lines of ionised and recombining hydrogen and collisionally excited doubly-ionised oxygen (especially Balmer-α and [OIII]λ5007 in the optical). However, this emission is several orders of magnitude fainter than the line emission seen from the interstellar gas. Nevertheless, within the last decades,

astronomers obtained spectacular emission-line images of galactic winds around star-forming galaxies in the not-so-distant Universe. These images revealed a variety of structures. Some of the feedback-driven winds appear bi-conical- or hourglass-shaped, while frothy networks of filaments and shell-like structures surround other galaxies.

We gained many insights regarding feedback mechanisms from such images. However, the observed sample of not-so-distant galaxies does not represent galaxies at earlier cosmological epochs, where transformative feedback processes are imagined to be most prevalent. Fortuitously, potential young universe analogues, where such transformative effects could be studied in detail, do exist in the present-day Universe, but at distances where it was, until recently, impossible to image the diffuse wind material. This situation only changed with the deployment of the Multi-Unit Spectroscopic Explorer (MUSE) instrument at one of the European Southern Observatory's Very Large Telescopes (mirror diameter: 8m) on Cerro Paranal in Chile. This instrument, an integral-field spectrograph, provides an unprecedented sensitivity for imaging faint emission-line structures in the Universe. Capitalising on this opportunity, we embarked on a programme to analyse early universe analogues observed with MUSE to map potential feedback effects.

Our latest analysis in this programme concerns the very extreme star-forming dwarf J1044+0353, and the results were astounding. J1044+0353 is a very tiny galaxy (diameter 7.100 light-years) at a distance of 170 million light-years. This extreme dwarf was initially discovered in the Sloan Digital Sky Survey in 2003. Due to its peculiarity, it has since been observed with many of the world's state-of-the-art telescopes (e.g., Keck, Subaru, or Hubble Space Telescope). These measurements already suggested extreme feedback effects, but our analysis now revealed the unexpected dimension of the expelled material (see Figure). The data clearly show that J1044+0353 is surrounded by seven giant elliptical arcs that exceeds the galaxy's extent by large. These arcs trace relatively thin and dense shells surrounding bubbles filled with hot and extremely diffuse gas. While a few of these bubbles appear to have popped, others remain remarkably intact. Morphologically, similar configurations were already known around star-forming galaxies in the not-so-distant Universe, but the newly discovered bubble structure is five times larger. In fact, classical analytical models of large-scale bubble formation due to the combined effect of supernovae fail to reproduce the properties of the shells surrounding J1044+0353.

Our analysis reveals that our current understanding of feedback processes remains limited. To comprehend how galaxy-scale winds driven by supernovae really work, we need to collect more images of diffuse gas around extreme star-burst galaxies. We do not yet know whether the structure around J1044+0353 is truly special or whether many more tiny galaxies may blow similar super-sized bubbles. We will therefore have to move away from single-object studies and aim at sample-based studies with MUSE. This will allow us

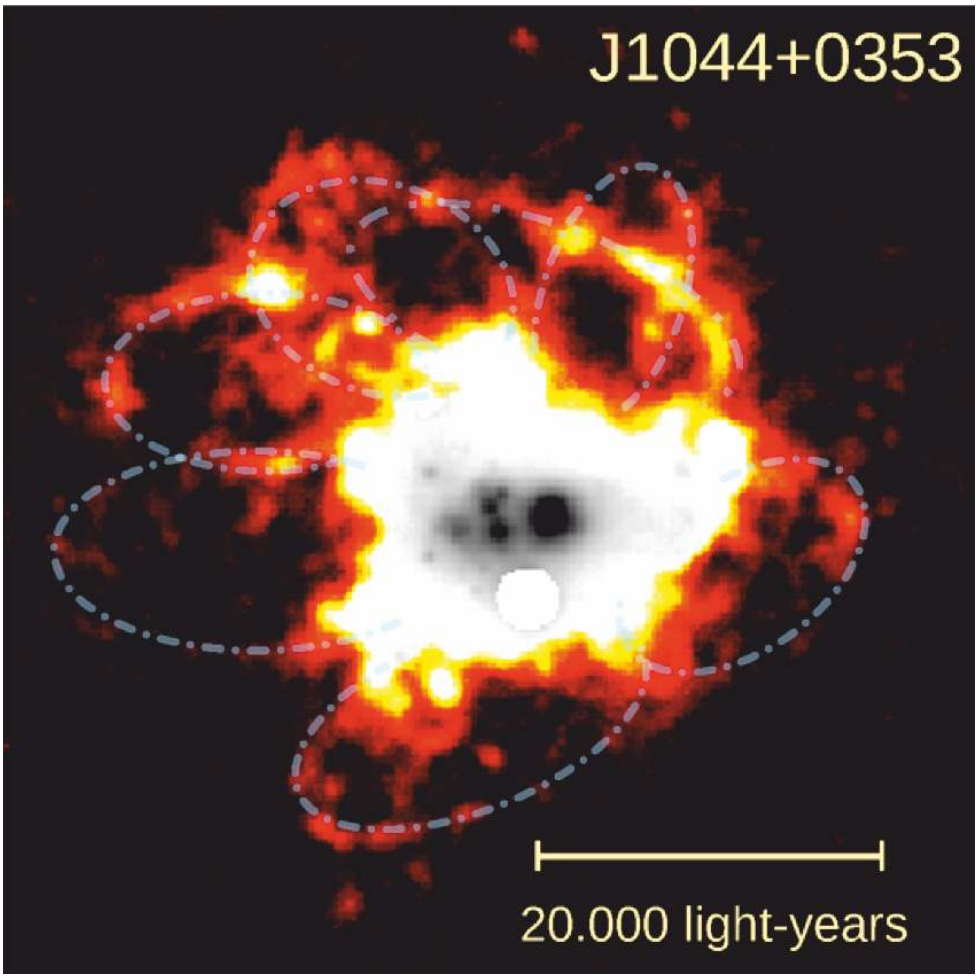

Figure 1: In the centre of the image, the stellar light of the galaxy J1044+0355 is shown in black. The galaxy is tiny (diameter 7100 light-years) and consists of several star clusters, each of which contains about 1 million stars. We have now discovered that the galaxy is surrounded by a more than 20,000 light year extended filamentary structure of diffuse ionised gas. This gas is detected in hydrogen Balmer-α optical line emission (wavelength = 656.3 nm) in a 1.5-hour exposure with the Multi Unit Spectroscopic Explorer on the 8 8-meter diameter telescope "Yepun" at the European Southern Observatory on Cerro Paranal in Chile. The detection is visualised in hues of bright yellow to red. These filaments connect along several elliptical loops, which are indicated with dot-dashed lines. These loops are the dense surfaces of bubbles that are likely blown by more than 50000 supernovae explosions in the last 20 million years.

(Image based on observations made with ESO Telescopes at the La Silla Paranal Observatory under programme ID 0103.B-0531)

to census extended line emission around star-bursting dwarfs. Moreover, we will soon complement the MUSE observations with deep 21cm observations, allowing us to map the circumgalactic neutral hydrogen around star-forming dwarfs. To this end, we are currently conducting observations with the MeerKAT radio telescope in South Africa and the GMRT in India. Ultimately, these endeavours shall deliver a more holistic picture of feedback from star-burst galaxies.

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Further Reading

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Clump-fed Black Hole Growth in the First Billion Years of the Universe

The efforts of past decades of observational astronomy have established the fact that every galaxy hosts a Supermassive Black Hole (SMBH) at their center. Although in the nearby Universe, these SMBHs make up a fraction of a percent of the total stellar mass of the galaxy, the strong correlations among the central stellar mass/kinematics and SMBH mass hint towards a co-evolution. This makes studying the evolution of SMBHs crucial for understanding galaxy evolution. The masses of SMBHs in the nearby universe can be explained well through gradual growth, considering their ample time. The problem arises when we find SMBHs very early in the Universe (i.e, at high redshifts (high-z)), as it becomes increasingly complex to explain these masses with the most popular models of SMBH growth. These high-z SMBHs usually do not follow the galaxy-SMBH correlations found at low-z, which suggests a rapid growth scenario compared to the host galaxy. With JWST finding these previously undiscovered SMBHs, thanks to its sensitivity, it is necessary to test these models of SMBH evolution using the real data.

As we see in the nearby Universe, galaxies appear to have very well-defined shapes and large-scale near-smooth morphology. This picture breaks down as we start to observe deep in space and time, when most galaxies were still in their infancy, their shapes are clumpy and irregular, far from being a regular spiral or elliptical. Although these star-forming clumps are present in the nearby galaxies, their size compared to the whole galaxy is much smaller than in the high-z galaxies, where they contribute significantly to the total stellar mass of the galaxy. Due to the heavier masses of these clumps, there is a larger force on them caused by the dark matter halo of the host galaxy. Some models took this line of thought and showed in simulations that these clumps could play a crucial role in feeding the central SMBH as they inspiral quickly to the center, and hence can explain the rapid growth at high-z. Here in this study, we tested this model on one such galaxy (GSz5BH), shown in zoom-in, which met all the criteria and has all the data available fit for testing such an interpretation. This galaxy hosts an SMBH of 30 million solar masses (~2% of the stellar mass of the host galaxy) at a time when the Universe was only one billion years old. In addition to the black hole, this galaxy has detected three massive star-forming clumps, a few kpc away from the AGN. We measure these clump masses using HST and JWST imaging data, and the motion of these