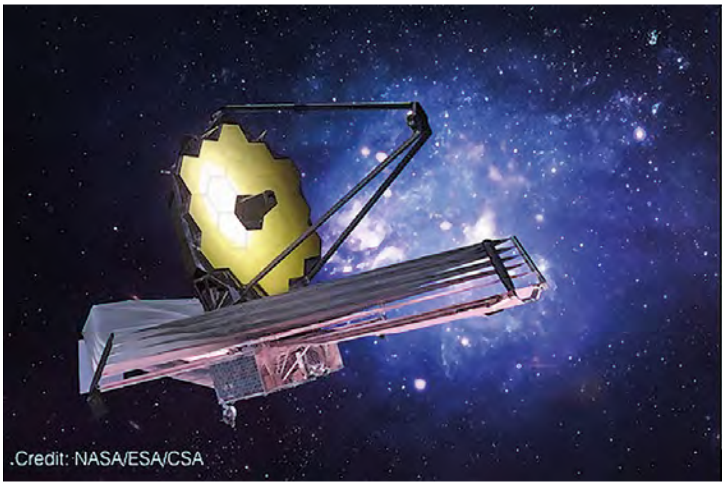

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GALAXY FORMATION AND EVOLUTION IN THE EARLY UNIVERSE: NEW RESULTS FROM JWST

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Since starting scientific operations over two years ago, JWST has revolutionised our understanding of galaxy formation and evolution in the early universe. To reconstruct that period, we observe very distant galaxies, which are so far away that the light that reaches us from them today was emitted at very early cosmic times.

▲ **FIG. 1:** Ultra-deep RGB composite image of the Hubble eXtreme Deep Field (HXDF) produced from JWST observations in different filters, with two examples of Halpha emitting galaxies at z>7 highlighted.

Galaxies around the Epoch of Reionisation

In that long trip, the light was redshifted by a factor (1+z), where z is the galaxy redshift. This is due to the expansion of the universe. As stars mostly emit photons at UV and optical wavelengths, we receive those of distant galaxies in the infrared, which is the wavelength domain in which JWST can observe. JWST's superb sensitivity is the result of the large collecting area of its 6.5m-diameter primary mirror. Thanks to it we are now identifying more and more distant galaxies. The current record holder is at z=14.3 (corresponding to about 300 million years after the Big Bang; [1]), but many new galaxies at z>7 have been discovered with JWST. This means that we can now start to probe galaxy evolution since the beginning of the so-called 'Epoch of Reionisation', the period when all the atomic hydrogen in the intergalactic medium became progressively ionised by the energetic UV radiation produced by the first stars and galaxies.

One of the main goals of JWST is to understand which kind of galaxies were responsible for Reionisation. These studies concluded that young, low stellar-mass galaxies mainly drove the Reionisation process (*e.g.* [2]), particularly those which are strong line emitters [3-5]. In the latter, the ionising photon production efficiency can directly be inferred from Balmer line luminosities. Particularly the Halpha line, emitted at rest-frame wavelength 6563 Angstroms, is the preferred tracer, as it is the brightest Balmer line and less affected by dust extinction. Halpha is shifted into the JWST NIRCam's observing window (0.6-5.0 micrometers) at z<7, while it enters the wavelength domain of the JWST Mid Infrared Instrument (MIRI; 5-28 microns) for galaxies at z>7 [6] (Fig. 1).

Detecting Halpha is also important because this spectral line is one of the most unbiased tracers of the galaxy ongoing star formation. The Halpha line is produced in the photospheres of massive O and B-type stars, which are short lived (typically a few million years). Until the advent of JWST, Halpha could only be directly detected up to z~3 mainly with ground-based telescopes. Now with JWST we can trace it at all redshifts, allowing us to measure the galaxy star formation rate in a consistent manner through the entire cosmic history.

Starburst Galaxies

In the local universe, most star-forming galaxies form their new stars at low rates. For example, the Milky Way is only forming about 1-2 new stars like the Sun per year. The bulk of their stellar masses has been formed in the past. Starburst galaxies, whose ongoing star formation rate (SFR) is much higher than their average past value, are rare. Indeed in the past (*i.e.*, at higher redshifts) the typical star formation rates of galaxies was higher, but the vast majority of relatively massive galaxies (Mstellar > 10^{10} Msun) are settled enough to already be forming stars at moderate rates. They are located in the so-called 'main sequence of star formation' (*e.g.* [7-9]), which means that their specific star formation rates (sSFR = SFR / Mstellar) are rather small.

The situation is different when one analyses distant lower stellar-mass galaxies [10]. The galaxy sSFR increases towards low stellar masses and increasing redshifts [11], so starbursts were much more common in the past amongst low stellar-mass galaxies. With the new, ultra sensitive JWST images we can now probe galaxies as small as the Milky Way satellites (with stellar masses 10^7 - 10^8 M_{sun}) up to high redshifts (z~7). We can now pinpoint, for galaxies of different stellar masses, at which moment in cosmic time the starburst mode lessened and most galaxies settled onto the star formation main sequence [12].

The new JWST results also indicate that, around the Epoch of Reionisation, the starburst mode was dominant (*e.g.* [13]), and this is the case amongst bright spectral line emitters, but also amongst other young, low stellar-mass galaxies whose line emission is not so prominent any more [14]. The origin of the starburst phenomenon is not completely clear. However, from theoretical models, it is known that single, gas accretion episodes can lead to the formation of tens of millions of solar masses in ~10 Myr, effectively producing that a ~ 10^7 M_{sun} galaxy doubles its stellar mass in such a short time [15][16].

Little Red Dots: star-forming galaxies or active galactic nuclei?

One of the most intriguing galaxy populations discovered by JWST at high redshifts are the so called Little Red Dots (LRDs) [17]. These are mostly faint, compact galaxies characterised by a flat spectrum at rest-frame UV wavelengths and a rising luminosity towards the infrared, producing the red colour. The spectra of tens of these sources show the presence of broad emission lines, indicative of nuclear (black-hole) activity (*e.g.* [18][19]). However, the black-hole masses derived for these objects are quite large, making difficult to explain how such objects could have been grown at such early cosmic times [20].

The active black-hole nature of LRDs has recently been scrutinised by some research groups, based on the faint (or none) X-ray emission of these objects [21] and the fact that high star formation rate densities could also lead to broad spectral line emission [22]. In addition, the nature of these sources has now become more intriguing after the discovery of more extended galaxies with similar photometric properties [23].

Conclusions

In its first years of operation, JWST has enabled multiple scientific discoveries in the field of early galaxy evolution. Actually, these discoveries have been so many and so fast that we are still struggling to provide a clear interpretation for all of them. The coming years will be devoted to follow up in detail these new galaxy populations, with JWST and other facilities (*e.g.*, ALMA and later the European Extremely Large Telescope). The final goal is to solve the puzzle of how the first steps of galaxy formation and evolution have happened in the early universe, allowing for the universe to be reionised and for galaxies to grow from small seeds to larger objects as we know them today. ■

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