



The Universe's 100th Birthday: Galactic Fireworks and Little Red Dots

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Astronomers build observatories, not experiments. Though funding for massive projects like the Hubble Space Telescope, or JWST, is justified with specific ideas about what science they may do, and their selection and design is inevitably dependent on those plans, they are multi-purpose, shared, instruments: the discoveries they make are often unanticipated, and even unrelated to their ostensible missions.

This has been a theme of my Gresham lectures, but it's been on my mind as the most exciting astronomical saga in years has unfolded. As I described last year, the infra-red sensitive JWST¹ has been spectacularly successful in capturing the faint light that reaches us from galaxies in the first billion years of cosmic history: these systems are more active, with plentiful star formation and surprisingly large central black holes, than many anticipated. However, in these deep images, astronomers have noted another population of sources. Small, star-like points, with the usual economy of phrasing they have been named LRDs: Little Red Dots. Are these some exotic form of galaxy? Something truly bizarre, like a zombie star? Or something local, the equivalent of dust on a window screen.

As the title of this lecture suggests, this is a particularly good time to be considering the form and structure of galaxies. It remains surprising to me that the idea that the basic constituent of the cosmos is the galaxy – a (normally) isolated system of a few hundred million stars – is so recent. The great writer and popularizer Agnes Clerke had the idea of galaxies beyond the Milky Way as a 'long-forgotten and discredited hypothesis' in 1904. In 1920, what has become known as the 'Great Debate' pitted astronomers Harlow Shapley and Heber Curtis against each other in discussion of the nature of the 'spiral nebulae' that we now know to be distant galaxies. Yet a decade later, systematic surveys with the great telescopes of the USA had begun the century-long task of mapping our Universe.

If you have to pick a single moment when our conception of the cosmos expanded, a good candidate would be Henry Norris Russell's address to the American Astronomical Society in Washington DC, on New Year's Day 1925. In it, he revealed the news – already leaked, conveniently, to the New York Times a few weeks earlier – that Edwin Hubble had shown that the Andromeda Galaxy was indeed a distant system². Shapley, the proponent of a smaller cosmos, said that Hubble had 'destroyed my Universe'.

¹ JWST was the subject of my last lecture last year: <https://www.gresham.ac.uk/watch-now/new-sky>

² This story is told in much more detail in my first ever Gresham lecture: <https://www.gresham.ac.uk/watch-now/galaxies-beyond>

If that result destroyed the idea of a cosmos consisting of just one galaxy, I'd place the birth of the Universe we have inhabited ever since with the publication, in 1926, of Hubble's systematic survey of what he describes as 400 extragalactic nebulae. Though he has measured the distance of only six of them, but making the assumption that they are all of the same brightness, he can describe what is a recognisably modern view of the cosmos: a Universe filled with galaxies, each weighing hundreds of millions of solar masses, separated by vast distances. The paper explicitly links these observations to solutions to Einstein's equations which describe a 'boundless yet finite Universe', and look forward to 'reasonable increases in the speed of plates and size of telescopes' so that 'it may become possible to observe an appreciable fraction of the Einstein universe.' (Hubble, 1926)

This single sentence set 20th century extragalactic astronomy on a path it would follow through at least three generations of new telescopes. Initial progress, particularly using the new and majestic Palomar 200" telescope after the Second World War, established the typical properties – the masses and luminosities, in particular – of nearby systems, but as astronomers probed deeper with better instrumentation and more ambitious programs they began to argue over another fundamental question. Was the distant (and therefore, the younger) cosmos the same as the one we see around us today? Or could they detect evolution?

This story is well told by Richard Ellis (see reference section) in a recent book. In parallel, a new sort of source had appeared in astronomer's images. First found in radio surveys in the early 1960s, 'quasi-stellar radio sources', or quasars, appeared in images sensitive to visible light as single points of light. With odd spectral features (mostly surprisingly broad lines), and a propensity to flicker rapidly, suggesting a source perhaps no bigger than the Solar System. The spectra of 3C 273, a radio source categorically associated with an optical counterpart by some careful observations during its occultation by the Moon, made clear that these were distant sources: these intriguing objects soon turned out to belong to the distant Universe.

Though some – including Maarten Schmidt, who had been responsible for taking that critical spectrum of 3C 273 – quickly grasped the implications³, suggesting that these must be very luminous objects indeed, arguments over the nature of the quasars persisted throughout the 1970s. Eventually, observers such as Jim Gunn found that these sources were embedded in 'fuzzy' surrounding galaxies, and the energy source had been identified as accretion onto a central black hole⁴. What started as an attempt to understand a new type of object had led to the opening up of a rich vein of phenomenology and new physics that we are still mining today. The distinction between 'quasar' and 'galaxy' has, for most purposes, fallen away as it became clear that all massive galaxies have a central black hole, and that in some circumstances these can switch between being powerfully accreting systems to a more quiescent state.

I've been thinking of the quasar story as news about the Little Red Dots made their presence felt in JWST images. After the telescope entered service in 2022, Dots showed up immediately. They can be seen in some of the first images, and a string of papers throughout 2023 catalogued them and argued about their properties⁵. As with quasars, while

³ Schmidt, 1963: '[an] explanation in terms of an extragalactic origin seems most direct and least objectionable.'

⁴ This idea was proposed surprisingly early, by Allan Sandage and Yakov Zeldovich in 1964, though it was ignored until Donald Lynden-Bell set out the principles of accretion in 1969. It took another few decades to build up the evidence that this exotic model actually works.

⁵ In keeping with the long tradition of astronomical names being assigned by accident, the first use of the term in the literature is by Langeroodi & Hjorth 2023, who argue that many of the 'Little Red Dots' are actually nearby stars.

researchers argued about their properties and nature – distant dusty starburst, or a growing black hole hidden in the centre of a galaxy – others wondered if they really could be as distant as they appeared. The argument that these things belong to the early Universe comes from their colour – the expansion of the Universe stretches light, redshifting galaxies. But anything this distant would have to be very bright indeed to be seen, something that was hard to reconcile, just as it had been for quasars, with the size of the point-like objects in the images. However, spectroscopy quickly demonstrated that these really were high-redshift, and hence distant systems.

But what were they? They seemed to have remarkably consistent properties. Though their red appearance is because of the cosmic redshift, they are also red in colour in the rest-frame – confusing, as active, star-forming, luminous galaxies should be blue, lit by their massive stars. On the other hand, with instruments sensitive to the ultra-violet, they are blue. And despite huge amounts of effort, no x-ray detections have been made. So we need a source of luminosity compatible with these results: not blue enough for stars (unless hidden in dust?) and not red enough for an uncovered Active Galactic Nucleus (an accreting black hole). (A good recent summary is Barro et al. 2025; see reference list).

Slowly, over the course of the last year, we have started to see spectra of substantial numbers of Dots. These have added to the mystery. As described by this excellent *Astrobit*es article (<https://astrobit.es.org/2024/11/22/balmer-breaks/>) from 2024, the presence of a feature in the spectrum called a Balmer Break initially suggested that there must be a multitude of hot stars present, enough to ionize the hydrogen gas which produces some of the spectral lines.

The problem is that the spectra can, with certain assumptions, constrain the number of such stars which need to be present to explain what's seen. As more extreme Dots showed up, the equations indicated that the Dots must have stars which collectively weight tens of billions of solar masses – orders of magnitude larger than the Milky Way, but formed within the first billion years of the cosmos.

This exciting prospect seems implausible. What about an active galactic nucleus? Well, this might work, with a big enough blanket of dust. This could possibly explain what's seen (see Inayoshi & Maiolino 2024), though then you need to explain how large black holes form, quickly, in the early Universe.

The theorists are on the case, with two sets of explanations. In one, just as now, black holes form via the sudden and violent death of massive stars in supernovae. The first population of stars in the Universe are expected to be massive, and if they are massive enough, and die early enough, then they could produce the population of black holes that we see. However, even if they get their starts as remnants of short-lived, hundred-solar-mass stars, they would have to grow quickly to reach the mass that we think might be needed to power a Little Red Dot.

A second set of possibilities involves bypassing the stellar stage altogether. If early galaxies – or a few early galaxies – have the right combination of density and temperature, they might form black holes directly, perhaps starting with something that weighs in at 100,000 or even a million solar masses. The problem is that the conditions that are required seem rather extreme, and are likely to be rare.

With no clear explanation, we probably shouldn't be surprised that more exotic explanations are becoming fashionable. 'Black hole stars' – black holes surrounded by an envelope of heated gas, rather than just a disk – are postulated by many. My favourite suggestion, though, is that we might be seeing the effects of 'quasi-stars' (Begelman & Dexter 2025). Here, a black hole is produced following via the collapse that follows a normal stellar

supernova, but instead of that being the end of the story, they live in a symbiotic relationship with the star. It shines on, but with a black hole at its heart, growing steadily even while the star continues to shine.

If this idea is right, JWST has discovered a completely new class of object. If not, then we've missed a type of galaxy that dominates the cosmic census in the Universe's early years. Either way, a suitable birthday present for the galaxy.

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References

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<https://ui.adsabs.harvard.edu/abs/1926ApJ...64..321H/abstract>

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<https://arxiv.org/abs/astro-ph/9903401>

The Little Red Dot literature is changing quickly. This is a complete set of papers with 'Little Red Dot' in the abstract: <https://tinyurl.com/LRDPapers>

An early LRD paper was Matthee et al., 2024, 'Little Red Dots: An Abundant Population of Faint Active Galactic Nuclei at $z \sim 5$ Revealed by the EIGER and FRESCO JWST Surveys', Astrophysical Journal, 963, 2, 129

A decent overview of spectroscopy which confirms these are distant sources is in Greene et al., 'UNCOVER Spectroscopy Confirms the Surprising Ubiquity of Active Galactic Nuclei in Red Sources at $z > 5$ ', 2024, Astrophysical Journal, 694, 1, 39

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