High velocity dispersion in a rare grand-design spiral galaxy at redshift $z = 2.18$

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Although grand-design spiral galaxies are relatively common in the local Universe, only one has been spectroscopically confirmed to lie at redshift $z > 2$ (HDFX 28; $z = 2.011$); and it may prove to be a major merger that simply resembles a spiral in projection. The rarity of spirals has been explained as a result of disks being dynamically 'hot' at $z > 2$ (refs 2–5), which may instead favour the formation of commonly observed clumpy structures⁶–⁹. Alternatively, current instrumentation may simply not be sensitive enough to detect spiral structures comparable to those in the modern Universe¹¹. At $z < 2$, the velocity dispersion of disks decreases¹², and spiral galaxies are more numerous by $z \approx 1$ (refs 7, 13–15). Here we report observations of the grand-design spiral galaxy Q2343-BX442 at $z = 2.18$. Spectroscopy of ionized gas shows that the disk is dynamically hot, implying an uncertain origin for the spiral structure. The kinematics of the galaxy are consistent with a thick disk undergoing a minor merger, which can drive the formation of short-lived spiral structures¹⁶–¹⁸. A duty cycle of $< 100$ Myr for such tidally induced spiral structure in a hot massive disk is consistent with its rarity.

Using infrared imaging data from the Hubble Space Telescope Wide-Field Camera 3 (HST/WFC3), tracing rest-frame $\sim 5000\AA$ stellar continuum emission (details in Supplementary Information), we found that Q2343-BX442 (hereafter BX442) is well resolved, with a total luminous radius, $R$, of $\sim 8$ kpc, prominent spiral arms, a central nucleus, and a faint companion located 11 kpc away in projection to the northeast. These morphological characteristics (see summary in Table 1) led us to tentatively identify BX442 as a late-type Sc grand-design spiral galaxy. Strikingly, BX442 is the only object to display regular spiral morphology in a sample of 306 galaxies with similar imaging¹⁶ at roughly the same redshift. We used the Keck/OSIRIS spectrograph in concert with the laser-guide-star adaptive optics (LGSAO) system to obtain integral field spectroscopy of nebular H$\alpha$ emission from ionized gas regions within BX442 at an angular resolution comparable to that of the HST imaging data ($

Figure 1 | Broadband and spectral emission-line morphology of BX442. a, b, HST/WFC3 F160W broadband morphology. In b, red lines show the locations of the northern (N), western (W) and eastern (E) spiral arms, core, and nearby satellite companion; green lines indicate the orientation of the best-fit inclined disk model (solid/dashed green lines represent opposite sides from the midplane); yellow lines represent the orientation of the long slit for previous Keck/NIRSPEC spectroscopy. The locations of these overlaid lines are defined visually; they are intended simply to guide the eye. (Alignment of individual images is discussed in Supplementary Information section 1.4.) c, Keck/OSIRIS H$\alpha$ emission-line flux map, overlaid with the red lines from b. Blue arrow shows the location of a bright star-forming clump in the northern arm. A visual rejection criterion roughly corresponding to a requirement for a signal-to-noise ratio of $> 3$ (details in Supplementary Information) was used to mask low-flux pixels. The field of view in each panel (oriented with north up and east to the left) is $3 \times 3$ arcsec, corresponding to $25.3 \times 25.3$ kpc at the redshift of BX442. In each panel, the red dot shows the full-width at half-maximum (FWHM) of the observational point-spread function.

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per second, although there is no indication that the highest-$\Sigma_{\text{SFR}}$ regions are the specific launching sites for galactic-scale outflows (see Supplementary Fig. 5), as recently proposed for a similar sample of galaxies.

Fitting a Gaussian profile to the H$\alpha$ emission line at each location across the galaxy, we determined that the velocity profile of BX442 (Fig. 2) is consistent with the rotating disk hypothesis, and exhibits a smooth gradient of $\pm 150$ km s$^{-1}$ along the morphological major axis, with flux-weighted mean velocity dispersion $\sigma_{\text{m}} = 66 \pm 6$ km s$^{-1}$ (after correcting for the instrumental resolution). The faint companion detected in the HST image is spectroscopically confirmed to lie within $100$ km s$^{-1}$ of the systemic redshift of BX442, but does not follow the global rotational velocity field, and may therefore represent a merging dwarf galaxy with mass a few per cent of that of the primary (as determined from the rest-frame $\sim 5,000$-Å luminosity ratio). The velocity dispersion of the ionized gas in BX442 is highest in the spiral arms, and appears to peak at $\sigma = 113 \pm 14$ km s$^{-1}$ in a bright star-forming clump in the northern arm.

We constructed a three-dimensional inclined disk model (details in Supplementary Information) that accounts for observational effects such as the delivered point-spread function, and determined that BX442 is consistent (reduced $\chi^2 = 2.3$) with being a rotating disk inclined at $42 \pm 10$° to the line of sight, with an inclination-corrected circular velocity $V_c = 234_{-20}^{+29}$ km s$^{-1}$ at the outer edge of the disk ($R \approx 8$ kpc). As inferred from our best-fit model, the vertical velocity dispersion of the disk is $\sigma_z = 71$ km s$^{-1}$ ($V_c/\sigma_z \approx 3$), indicating that the system is geometrically thick, with a scale height $h_z = \sigma_z^2/(2\pi G M) = 0.7$ kpc, comparable to those of similarly massive systems studied in the literature.

Contrary to expectations, our observations of BX442 indicate both that dynamically hot $z \approx 2$ disk galaxies can form spiral structure, and that such structure can easily be detected with current-generation instruments such as HST/WFC3. Indeed, despite its high velocity dispersion, the surface density of BX442 is sufficiently high that the Toomre parameter $Q \approx 1$ throughout most of the disk (details in Supplementary Information), suggesting that BX442 is susceptible to spontaneous formation of spiral structure. Galaxies with physical properties similar to those of BX442 are not remarkably uncommon at $z \approx 2$; large samples of galaxies with similar physical characteristics have been studied using high-angular-resolution imaging, integral-field spectroscopy, or both. In particular, 27 galaxies in the recent morphology survey from which BX442 was drawn have stellar masses within a factor of two of its mass, 10 of which also have similar half-light radii, star-formation rates, dust contents and stellar population ages. None of these other systems has clear spiral structure, indicating either that the triggering mechanism is relatively rare or that the duty cycle of the spiral pattern is extremely short.

Perhaps the most obvious distinction of BX442 is that it appears to be experiencing a close-passage minor merger, which numerical simulations and theoretical calculations suggest can be a natural means of producing grand-design spiral patterns in galactic disks, even for mass ratios as modest as a few per cent$^{17}$. Indeed, many of the best known grand-design spiral galaxies in the nearby Universe (for example, M51, M81 and M101) are observed to have nearby companions, and small satellites such as the Sagittarius dwarf galaxy may even be partly responsible for producing spiral patterns in our own Milky Way galaxy$^{28}$. We test the plausibility of the merger-induced hypothesis by comparing BX442 to a $z \approx 2$ model galaxy selected from a set of extremely high-resolution $N$-body smoothed particle hydrodynamic simulations (details in Supplementary Information). Although the model disk spontaneously forms flocculent spiral structure in isolation, the lifetime of grand-design spiral patterns induced by the merging companion is generally less than half a rotation period (that is, $\leq 100$ Myr, or $\Delta z \leq 0.08$ for BX442).

Such a mechanism may therefore naturally explain why visible spiral structure at $z \approx 2$ is so rare: not only must a galaxy be sufficiently massive to have stabilized the formation of an extended disk$^{30}$, but this disk must then be perturbed by a merging satellite sufficiently massive and properly oriented to excite an observable grand-design spiral structure.

**Figure 2** | Kinematic velocity and velocity-dispersion maps of BX442. a, d, Observed relative velocity (a) and velocity dispersion (d) (uncorrected for instrumental resolution), recovered from fitting Gaussian emission-line profiles to the H$\alpha$ emission in each spatial pixel. The total integration time was $13$ h, with a point-spread function (PSF) width of $0.25$ arcsec (corresponding to $\approx 2$ kpc at the redshift of BX442). b, e, Best-fit inclined-disk models of the relative velocity (b) and velocity dispersion (e), after convolution with the observational PSF and Keck/OSIRIS spectral resolution. c, f, Residuals after subtraction of the best-fit models from the observed velocity (c) and velocity dispersion (f) fields. The residual values are given in units of the observational uncertainty: $1\sigma$ corresponds to $17$ km s$^{-1}$ for the line-of-sight velocity, and to $14$ km s$^{-1}$ for the line-of-sight velocity dispersion. Black lines indicating the spiral disk structure are overlaid from Fig. 1b; these lines indicate that the kinematic centre of BX442 is offset from the apparent nucleus of the continuum flux by $\approx 2$ kpc, owing in part to the uncertainty in image registration between the HST/WFC3 and Keck/OSIRIS data (see discussion in Supplementary Information). Red dots show the FWHM of the observational point-spread function.

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pattern. Further, this spiral must be observed in the narrow window of time for which its strength is at a maximum, and must be oriented sufficiently close to face-on that the pattern is recognizable.

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See Supplementary Information for details. SFRsed and SFRw are star-formation rates derived from stellar population modelling and inversion of the Schmidt–Kennicutt law, respectively.

* Decomposing the central nucleus from the surrounding disk using a model of the HST/WFC3 point-spread function indicates that the nuclear emission region contributes ~10% of the total rest-frame ~1,000 Å continuum flux, and has a small redshift radial profile index n = 4 and a half-light radius r = 1.5 kpc, consistent with galactic bulges in nearby disk galaxies.

† Fourier phase-profile analysis of the spiral arms indicates substantial power in the m = 2 and m = 3 symmetry modes, corresponding to a three-armed spiral pattern (in which one arm is foreshortened by the inclination to the line of sight) with opening pitch angle $\alpha = 37^\circ \pm 6^\circ$.

‡ Spiral arm/interarm surface brightness differentiation, in AB magnitudes per square arcsecond.

Table 1 | Physical characteristics of Bx442

| Characteristic          | Value |
|-------------------------|-------|
| Right ascension (J2000) | 23 h 46 m 19.35 s +12° 48' 00.0" |
| Declination (J2000)     | 2.1765 ± 0.0001 |
| Redshift*               | 6.175 ± 1.000 Myr |
| Lookback time           | 2 $\times$ 10^{10} M_{\odot} |
| Stellar mass            | 5.2 $\times$ 10^{37} M_{\odot} yr^{-1} |
| Gas mass                | 45 M_{\odot} yr^{-1} |
| Age                     | 1,100 ± 100 Myr |
| SFRsed                  | 10% |
| Inclination             | 42 ± 10° |
| Pitch angle‡            | 37 ± 6° |
| Spiral arm contrast‡    | 1 AB arcsec^{-2} |
| Circular velocity       | 25–29 km s^{-1} |
| Optical radius          | 8 kpc |
| Velocity dispersion     | 71 ± 1 km s^{-1} |
| Hubble type             | Sc |

Supplementary Information is linked to the online version of the paper at www.nature.com/nature.

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