SCENIC+)[10] can suggest regulators and trait changes of interest that might have been missed, from data that are often available already. Moreover, testing the tool's predictions is easier than ever, thanks to gene-editing tools such as CRISPR–Cas9 and ever-cheaper single-cell genomic assays.

Even in the well-studied axial mesoderm, CellOracle identified previously unknown regulators and predicted new roles for previously identified regulators. The authors' predictions can be browsed online, and their tool is freely available (www.celloracle.org). It has already been used by the authors to identify regulators of cell reprogramming in a tissue called the endoderm[11]. Other groups have used it to predict regulators of immune-cell identity[12]; to further explore known regulators of the formation of cell types in the thymus[13], immune system[14], cartilage and bone[15]; and to study progenitors of an embryonic tissue called the neuromesoderm[16].

My own prediction is that approaches such as CellOracle will hasten our understanding of the regulatory networks that determine cell identity. Let us hope that, in doing so, they will accelerate development of medical interventions that manipulate these networks. But future users beware: just as, in Greek mythology, Apollo had to slay Python to establish his oracle at Delphi, you, too, will have to conquer Python (in this case, the scripting language) before you can use CellOracle.

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1. Kamimoto, K. *et al. Nature* **614**, 742–751 (2023).
2. Davidson, E. H. *et al. Science* **296**, 1669–1678 (2002).
3. Simões-Costa, M. & Bronner, M. E. *Development* **142**, 242–257 (2015).
4. Nguyen, H., Tran, D., Tran, B., Pehlivan, B. & Nguyen, T. *Brief. Bioinform.* **22**, bbaa190 (2021).
5. Halpern, M. E. *et al. Development* **121**, 4257–4264 (1995).
6. Wontakal, S. N. *et al. PLoS Genet.* **7**, e1001392 (2011).
7. Moreau-Gachelin, F. M., Tavitian, A. & Tambourin, P. *Nature* **331**, 277–280 (1988).
8. Dal-Pra, S., Thisse, C. & Thisse, B. *Dev. Biol.* **350**, 484–495 (2011).
9. Seiliez, I., Thisse, B. & Thisse, C. *Dev. Biol.* **290**, 152–163 (2006).
10. Bravo, C. *et al.* Preprint at bioRxiv https://doi.org/10.1101/2022.08.19.504505 (2022).
11. Kamimoto, K. *et al. Stem Cell Rep.* **18**, 97–112 (2023).
12. Chopp, L. B. *et al. Immunity* **53**, 1182–1201 (2020).
13. Magaletta, M. E. *et al. Nature Commun.* **13**, 457 (2022).
14. Ravi, V. M. *et al. Nature Commun.* **13**, 925 (2022).
15. Herpelinck, T. *et al.* Preprint at bioRxiv https://doi.org/10.1101/2022.03.14.484345 (2022).
16. Argelaguet, R. *et al.* Preprint at biorxiv https://doi.org/10.1101/2022.06.15.496239 (2022).

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Forum: Astronomy

JWST opens a window on exoplanet skies

An unprecedented glimpse of a distant planet reveals clues about how it might have formed. Scientists explain why it's a win for atmospheric chemistry, and celebrate the technology that made it possible. **See p.649, p.653, p.659, p.664 & p.670**

The papers in brief

- **NASA's James Webb Space Telescope (JWST) was launched in December 2021 and now orbits the Sun, some 1.5 million kilometres from Earth.**
- **Early data released last year confirm that this is an ideal vantage point for investigating exoplanets — the distant worlds that orbit stars other than the Sun.**
- **Five papers in *Nature* report analyses profiling the atmospheric chemistry of WASP-39b, a hot exoplanet with a Saturn-like mass.**
- **The studies settle questions about this exoplanet's atmosphere, and showcase the power and versatility of JWST.**

Julia V. Seidel & Louise D. Nielsen
Composition and origins of far-flung worlds

Rustamkulov *et al.*[1] (page 659), Alderson *et al.*[2] (page 664), Feinstein *et al.*[3] (page 670), Batalha *et al.* (page 649) and Ahrer *et al.*[5] (page 653) used three different instruments on board JWST — each with its own advantages and shortcomings — but reported largely complementary results (Fig. 1). In all five investigations, the teams found that elements heavier than hydrogen and helium are more abundant in the atmosphere of WASP-39b than they are in the Sun, whereas the ratio of carbon to oxygen is lower than that of the Sun and commensurate with that of Saturn. These findings offer crucial information about the planet's formation, the basic composition of its atmosphere and its potential to host life.

The carbon/oxygen ratio of an exoplanet's atmosphere is a telltale sign of where the planet formed[6]. This is particularly useful in the case of giant planets that are close to their host stars, because their formation mechanism has been an open question since the first exoplanet was found. The ratio measured for WASP-39b indicates that the planet might have formed at a location beyond the system's water-ice line — the distance from the host star at which it is cold enough for compounds such as water and carbon dioxide to condense into solid ice. At this location, the planet could have accreted the oxygen-rich solids measured by JWST, before migrating inwards to its current position.

The sulfur/oxygen ratio is another piece in the puzzle of planetary formation. But the sulfur content of an exoplanet's atmosphere is intriguing for another reason. Sulfur dioxide is much like the protective ozone in Earth's atmosphere: it is produced during chemical reactions that are triggered by ultraviolet radiation from the host star[7]. Rustamkulov *et al.* and Alderson *et al.* both detected sulfur dioxide in the atmosphere of WASP-39b. This observation marks the first direct evidence of light-induced (photochemical) reactions in an exoplanet atmosphere — a milestone in the quest for a truly habitable planet.

Much work remains to be done to probe the limits of this habitability. However, the finding is a step towards understanding how photochemistry protects exoplanetary surfaces from high-energy irradiation. It also tightens constraints on the parameters used in models of planetary formation. Both advances pave the way to future observations of planets that are similar to Earth.

Part of these efforts involve profiling the characteristics of the exoplanetary atmosphere itself. By comparing the measured chemical abundances with those of several cloud models, Feinstein *et al.* determined that the clouds of WASP-39b are broken up along the day–night terminator, the line that separates day and night on a planet. Such cloud structure has previously been associated with other hot exoplanets that have masses similar to that of Jupiter[8].

Further analysis of JWST data could reveal even more information about the formation location, cloud composition and photochemistry of WASP-39b. High-resolution ground-based observations will provide crucial constraints on the chemical content of its atmosphere – its potassium and sodium, for example, and the dynamic processes with which these chemical elements are associated. Indeed, the current construction of several extremely large telescopes on Earth is promising for our understanding of alien atmospheres – because JWST's impressive sensitivity can then be married with the high spectral and spatial resolution achievable from the ground.

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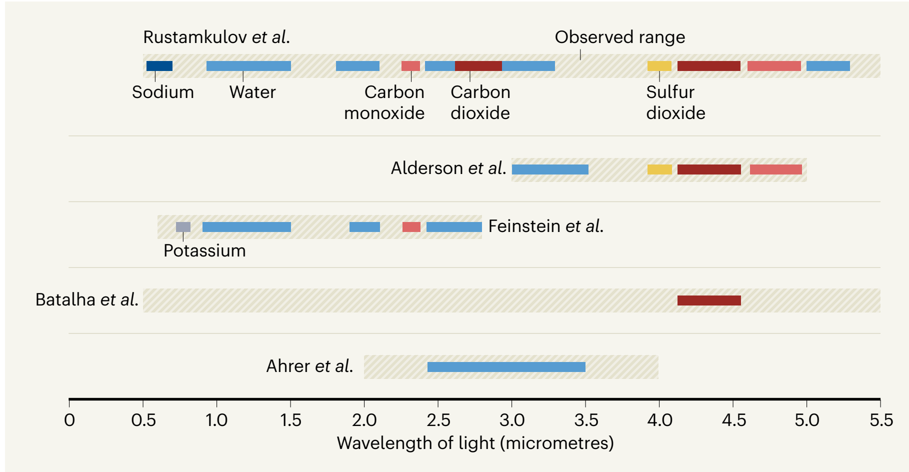

Figure 1 | Atmospheric chemistry from afar. Five papers report analyses that use the James Webb Space Telescope (JWST) to deduce the chemical composition of the atmosphere of the distant planet WASP-39b. The analyses mapped the atmosphere's transmission spectrum, which indicates how well light at various wavelengths permeates this atmosphere. The authors of each paper accessed a specific wavelength range by using one of three instruments (or configurations): Rustamkulov *et al.*[1], Alderson *et al.*[2] and Batalha *et al.*[4] used the Near Infrared Spectrograph; Feinstein *et al.*[3] used the Near Infrared Imager and Slitless Spectrograph; and Ahrer *at al.*[5] used the Near Infrared Camera. The studies revealed signatures of water, carbon dioxide, carbon monoxide, sodium and potassium; determined the properties of clouds; and uncovered evidence of sulfur dioxide. These findings are crucial for understanding the atmospheric processes occurring in WASP-39b and how and where the planet formed. (Adapted from graphic at go.nature.com/3ddesjg.)

Subhajit Sarkar
Exceptional data from an extraordinary telescope

The chemistry of an atmosphere is revealed in its 'transmission spectrum', which indicates how well light at various wavelengths can permeate the gas surrounding an exoplanet. This is typically obtained using a technique known as transit spectroscopy, an approach that involves monitoring changes in the intensity of starlight at discrete wavelengths as a planet transits its host star. Although this method has previously been used to study the atmosphere of WASP-39b (ref. 9), the present papers showcase the remarkable precision and quality of the data obtained with JWST, revealing the telescope's tremendous potential – and highlight the challenges to come.

The wavelength ranges of the three instruments used in the studies are all in the near infrared, the range in which one expects to find spectral features of the key atmospheric molecules reported. But each instrument has different configurations that enable access to different wavelength ranges and spectral resolving powers. Rustamkulov *et al.*, Alderson *et al.* and Batalha *et al.*[4] used two configurations of an instrument called the Near Infrared Spectrograph; Feinstein *et al.* used the Near Infrared Imager and Slitless Spectrograph; and Ahrer *et al.*[5] used a device known as the Near Infrared Camera. Between them, the teams observed light with wavelengths spanning 0.5 to 5.5 micrometres (Fig. 1).

This huge wavelength coverage makes possible the extraordinary scientific results obtained by JWST and is a much larger range than that of the Hubble Space Telescope, with which previous WASP-39b spectra were obtained[9]. The spectral resolution of JWST is also more powerful than that of its predecessor. Furthermore, JWST's primary mirror has a diameter of 6.5 metres compared with Hubble's 2.4 metres (see go.nature.com/3jhjfzu) – an increase that boosts the signal-to-noise ratio, enabling the instruments' exquisite precision.

Models for exoplanetary atmospheres have long been put forward to interpret the spectra[10], but without sufficient quality of data with which to refine and constrain these models, the spectra can be interpreted in different ways. The high quality of the data reported in these studies is therefore crucial to nailing down the details of WASP-39b – including everything from how it was formed to how its clouds behave.

Various data-processing algorithms were used for each instrument to traverse the complex path from raw data to the final spectrum. And although these efforts returned mostly similar results, the diverse approaches show that there is no consensus yet on the optimal way to process JWST data – indeed, there is much still to learn. Some problems have already begun to be addressed in these initial studies, including how best to manage pixels that are saturated[1] (giving unreliable signals), and what to do when mirror segments spontaneously tilt during observation[2].

Further solutions will be developed as our understanding of the instruments improves with time, but as a first test of JWST's performance, the results of these studies are very exciting. The findings are also encouraging for research beyond that of exoplanetary atmospheres. In particular, the WASP-39b successes show the ability of JWST to deliver data of exceptional quality, which will enhance our understanding of the early Universe, galaxies and star formation, as well as the search for life. There is now little doubt that JWST will deliver on its promise to transform astronomy – and, more specifically, exoplanet science – in the next decade.

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1. Rustamkulov, Z. *et al. Nature* **614**, 659–663 (2023).
2. Alderson, L. *et al. Nature* **614**, 664–669 (2023).
3. Feinstein, A. D. *et al. Nature* **614**, 670–675 (2023).
4. JWST Transiting Exoplanet Community Early Release Science Team (Batalha, N. M. *et al.*) *Nature* **614**, 649–652 (2022).
5. Ahrer, E.-M. *et al. Nature* **614**, 653–663 (2023).
6. Öberg, K. I., Murray-Clay, R. & Bergin, E. A. *Astrophys. J.* **743**, L16 (2011).
7. Tsai, S.-M. *et al.* Preprint at https://arxiv.org/abs/2211.10490 (2022).
8. Parmentier, V., Fortney, J. J., Showman, A. P., Morley, C. & Marley, M. S. *Astrophys. J.* **828**, 22 (2016).
9. Wakeford, H. R. *et al. Astron. J.* **155**, 29 (2018).
10. Madhusudhan, N. *Annu. Rev. Astron. Astrophys.* **57**, 617–663 (2019).

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