connected to mergers of compact objects, rather than to the collapse of massive stars.

On 11 December 2021, the Swift observatory detected another bright, long γ-ray burst with high intensity at all wavelengths, the source of which was a relatively close 350 megaparsecs away from Earth. The optical and infrared light emitted far exceeded that expected from the standard afterglow of the γ-ray burst. This afterglow is produced by a jet of relativistic particles, which are particles travelling at close to the speed of light, interacting with the surrounding medium. Troja *et al.* and Rastinejad *et al.* attribute this excess to a kilonova, because it is consistent with theoretical models of mergers, and its luminosity, duration and colours are similar to those of GW170817. In fact, this burst resembles a short γ-ray burst in all aspects except its duration.

This discovery begs the question of how the merger of two neutron stars could have given rise to such a long emission — a pulse of 13 seconds, followed by a pulse of lower intensity lasting another 55 seconds. One possibility is that a compact remnant of the merger (a black hole) powered a jet by accreting material from a temporary disk of debris from the collision. But the larger the disk, the longer the burst, and neutron-star mergers produce small, compact disks that are unable to sustain γ-ray bursts lasting longer than a second[9].

Yang *et al.* propose that the duration of the first pulse is long because it is associated with a large accretion disk surrounding a spinning neutron star with a very strong magnetic field (a proto-magnetar) that formed when a white dwarf merged with a neutron star. By contrast, the extended emission shows a different spectrum that suggests it was powered by a relativistic wind that extracted the rotational energy of the proto-magnetar. This scenario is not uncommon and has been proposed to explain the extended emission observed in a substantial fraction of short γ-ray bursts[10]. Indeed, the idea that a proto-magnetar is involved in GW170817 has not been ruled out[11,12].

Previously, the only known electromagnetic signature of a kilonova was the optical infrared flash. But Mei *et al.* found that the kilonova is also evident in the appearance of more photons than expected in the gigaelectronvolt energy range. This excess is produced by the same population of relativistic electrons that emits the afterglow of the γ-ray burst and that boosts the optical photons of the kilonova at high energies.

Other distinctive features of kilonovae have been proposed in the past, but have so far eluded detection. For example, ejecta from the merger are expected to produce shocks when they interact with the interstellar material, leading to faint emissions at radio to X-ray wavelengths that peak several years after the merger[13]. Ongoing monitoring of GW170817 (ref. 14) with existing observatories and a sample of short γ-ray bursts[15] has not detected such components. The low luminosity of the expected emission would require observatories with improved sensitivity, such as that promised by the Advanced Telescope for High-ENergy Astrophysics (Athena), the European Space Agency's X-ray observatory mission[16].

Future observatories might also reveal the spectral features produced by the decay of the radioactive nuclei that are generated in mergers[16,17]. Understanding the signatures of kilonovae at different wavelengths would enable an increase in the number of mergers detected through both gravitational waves and electromagnetic signals. Such joint efforts would hone the many merger models used to estimate the mass, composition and velocity of ejecta — data that are key to theories touting neutron-star mergers as the main source of heavy metals in the Universe.

Yang and colleagues' proposed scenario suggests that the kilonova emission is powered by a large amount of energy from the proto-magnetar, because mergers between neutron stars and white dwarfs are not expected to yield much neutron-rich material[18]. By contrast, a neutron-star merger requires limited, if any, energy from a magnetar[1,2]. It remains to be seen which scenario is correct, but any extra energy should boost the long-term radio emission in a way that might soon be detectable[15]. Another means of distinguishing the most plausible scenario involves the effectiveness of the accretion disk in supporting a long γ-ray burst, because the disk associated with the merger of a white dwarf and a black hole might not be capable of doing so[19].

The next campaign for the Earth-based gravitational wave laboratories Laser Interferometer Gravitational-Wave Observatory (LIGO), the Virgo interferometer and the Kamioka Gravitational Wave Detector (KAGRA) is planned for 2023 and 2026, and is expected to uncover tens to hundreds of neutron-star mergers[20]. About 10% of these mergers could be associated[1] with the strange hybrid γ-ray bursts reported in the four papers. This would mean that these events had been detected by both gravitational waves and electromagnetic emission, at least in cases in which the progenitor comprises two neutron stars. The gravitational-wave emission for the merger of a white dwarf and a neutron star would be too low for LIGO and Virgo to detect. But with so many pieces of the puzzle coming together, it won't be long before the origin of these peculiar flashes is revealed.

Luigi Piro is at the Istituto di Astrofisica e Planetologia Spaziali, INAF, 00133 Rome, Italy.
e-mail:luigi.piro@inaf.it

1. Troja, E. *et al. Nature* **612**, 228–231 (2022).
2. Rastinejad, J. C. *et al. Nature* **612**, 223–227 (2022).
3. Mei, A. *et al. Nature* **612**, 236–239 (2022).
4. Yang, J. *et al. Nature* **612**, 232–235 (2022).
5. Galama, T. J. *et al. Nature* **395**, 670 (1998).
6. Abbott, B. P. *et al. Astrophys. J.* **848**, L13 (2017).
7. Pian, E. *et al. Nature* **551**, 67–70 (2017).
8. Gehrels, N. *et al. Nature* **444**, 1044–1046 (2006).
9. Fryer C. L. *et al. Eur. Phys. J. A* **55**, 132 (2019).
10. Metzger, B. D., Quataert, E. & Thompson, T. A. *Mon. Notices R. Astron. Soc.* **385**, 1455–1460 (2008).
11. Metzger, B. D. *et al. Astrophys. J.* **856**, 101 (2018).
12. Piro, L. *et al. Mon. Notices R. Astron. Soc.* **483**, 1912–1921 (2019).
13. Nakar, E. & Piran, T. *Nature* **478**, 82 (2011).
14. Troja, E. *et al. Mon. Notices R. Astron. Soc.* **510**, 1902–1909 (2022).
15. Ricci, R. *et al. Mon. Notices R. Astron. Soc.* **500**, 1708–1720 (2021).
16. Piro, L. *et al. Exp. Astron.* **54**, 23–117 (2022).
17. Korobkin, O. *et al. Astrophys. J.* **889**, 168 (2020).
18. Bobrick, A. *et al. Mon. Notices R. Astron. Soc.* **510**, 3758–3777 (2022).
19. Narayan, R. *et al. Astrophys. J.* **557**, 949 (2001).
20. Petrov, P. *et al. Astrophys. J.* **924**, 54 (2022).

The author declares no competing interests.

Climate change

A plastic container for carbon emissions

Sangwon Suh & André Bardow

Modelling reveals that the carbon emissions associated with plastics could be negative by 2100 under a strict set of technological and socio-economic conditions — including increased recycling and plant-derived production. **See p.272**

The direct effect of plastics on the marine ecosystem has attracted global attention. However, the production and disposal of plastics are also a concern, because these processes release more climate-warming gases annually than does global aviation[1]. And these emissions are increasing: the growing global appetite for plastics is expected to result in a doubling of their associated carbon emissions by 2050. Such an increase would prevent us from achieving net-zero emissions, a target that is widely held to be necessary to protect the planet's ability to support life (see go.nature.com/3u7uiqc). On page 272, Stegmann *et al.*[2] provide a road map for avoiding this future by examining the entire life cycle of plastics in the context of various strategies for mitigating climate change.

The good news is that it is technically possible to produce and dispose of plastics with net-zero – or even negative – carbon emissions, using technologies that already exist[3,4]. However, the future deployment of such approaches has not been modelled with respect to socio-economic and technological factors[5], such as demography, income, the prices of energy and carbon, and the efficiencies of recycling technologies. These factors are crucial, because they affect the economic competitiveness of the technologies, as well as their carbon balance.

Stegmann and colleagues' study fills this gap by modelling the future of the plastics industry using a baseline 'middle of the road' socio-economic pathway (see go.nature.com/3uvdbgs). Their model then considers how specific changes to this pathway could lead to plastics having negative carbon emissions, while limiting the global mean temperature increase to 2 °C by the end of the century.

So how does it work? The problem of global climate change is largely about where to store carbon among Earth's four compartments: the atmosphere, biosphere, hydrosphere and geosphere. Storing carbon in the atmosphere alone causes climate change. But there is a sizeable fifth compartment in which carbon can be stored: the technosphere (comprising all the technological objects manufactured by humans, as well as our social and professional systems). Plastics are made mainly from carbon that comes from crude oil and natural gas, but they can also be produced using biomass, which draws carbon from the atmosphere. Through the conversion of biomass to plastics, this carbon is transferred from the biosphere to the technosphere, where it remains for a long time[6], either in use (for example, in building materials) or in secure landfill.

Therefore, Stegmann and colleagues demonstrate that, by substituting oil with biomass as a feedstock for plastics, and using our enormous appetite for plastics[7] to create a vessel for storing carbon, humans could use the global production of plastics to remove carbon from the atmosphere. They show that increased recycling would further reduce the reliance of future plastics on biomass feedstock, energy and space for landfill.

The true value of the study lies in its ability to offer insights into the socio-economic and technological conditions under which plastics turn into a carbon sink. To achieve this, the authors used a framework developed previously by members of the same team[8] to model the life cycle of plastics, from production to disposal. They first assessed how this model behaved in the baseline scenario, and examined how it would change with an increase in the price of carbon emissions, eliciting a global mean temperature increase of up to 2 °C. They then looked at other changes that promote circular-economy strategies, such as recycling and renewable-energy use, as well as a scenario that prioritizes biomass use in this circular economy.

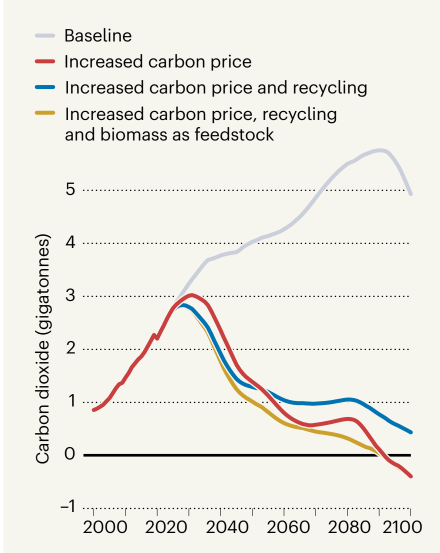

Figure 1 | Carbon balance of the plastics industry. Stegmann *et al.*[2] modelled the life cycle of plastics (from production to disposal) in the context of four scenarios for climate-change mitigation. Their baseline scenario was a 'middle of the road' socio-economic pathway (see go.nature.com/3uvdbgs). They then examined the effects of increasing the price of carbon emissions, incentivizing recycling and renewable-energy use, and prioritizing the use of biomass as a feedstock for plastics production. In two of the four scenarios, the plastics industry is forecast to have net negative carbon emissions before 2100. (Adapted from Fig. 3 of ref. 2.)

Through their analysis, Stegmann *et al.* show that plastics could achieve negative carbon emissions by the end of the century (Fig. 1), but only under a certain set of conditions – and they are tough to meet. They include implementing a globally uniform carbon-pricing scheme; offering up to 30% subsidies for companies using biomass to produce plastics; and mandating that the yields of key recycling technologies are increased by up to 20%. Each of these conditions is a tall order on its own. In that sense, more than anything else, the study highlights the magnitude of challenge that lies ahead.

As the authors point out, however, their results should be interpreted with caution. For example, their baseline scenario is intended to represent a 'business as usual' pathway, in which future behaviours largely follow historical trends. But many of the conditions they impose, including globally uniform carbon pricing, fall a long way outside this pathway. In our view, the friction between these two sets of assumptions – that nothing will change and everything will change – limits the extent to which policy-relevant interpretations can be drawn directly from the authors' results.

Future research will need to address the unintended impacts of storing carbon as plastics in the technosphere. The authors' scenario assumes that plastics production will double in volume by 2050, which will help to turn the industry carbon negative by increasing the carbon stock in the technosphere. Increased throughput, however, might exacerbate other problems, including the effect that plastics have on marine life. The extra demand for biomass could also escalate the competition for arable land, which is already stressed by the production of feed, fuel and food, and could lead to increased use of agrochemicals and fertilizer.

Finally, to make the authors' recycling and biomass goals attainable, materials and processes will have to be improved. This includes redesigning polymers to make them more amenable to recycling than those currently in use, and updating the processes for both recycling and biomass conversion. Such engineering-level details will need to be incorporated into future models.

It seems plausible that plastics could become a carbon sink in future. But will they? In our opinion, the answer hinges mainly on society's ability to create a socio-economic and political landscape that facilitates the transition, rather than on the development of necessary technologies. It remains unclear why global efforts can facilitate the conditions necessary to overcome some global environmental problems, such as ozone-layer depletion, but not others – yet. What can science do to help us understand the barriers to creating such conditions? Answers to these questions will be crucial for turning possibility into reality, and Stegmann and colleagues' study is a key step in this process.

Sangwon Suh is in the Bren School of Environmental Science and Management, University of California, Santa Barbara, Santa Barbara, California 93106, USA.
André Bardow is in the Department of Mechanical and Process Engineering, ETH Zurich, 8092 Zurich, Switzerland.
e-mails: suh@bren.ucsb.edu; abardow@ethz.ch

1. Zheng, J. & Suh, S. *Nature Clim. Change* **9**, 374–378 (2019).
2. Stegmann, P., Daioglou, V., Londo, M., van Vuuren, D. P. & Junginger, M. *Nature* **612**, 272–276 (2022).
3. de Oliveira, C. C. N., Zotin, M. Z., Rochedo, P. R. R. & Szklo, A. *Biofuels Bioprod. Biorefin.* **15**, 430–453 (2021).
4. Meys, R. *et al. Science* **374**, 71–76 (2021).
5. Rogelj, J. *et al. Nature Clim. Change* **8**, 325–332 (2018).
6. Chamas, A. *et al. ACS Sustainable Chem. Eng.* **8**, 3494–3511 (2020).
7. Geyer, R., Jambeck, J. R. & Law, K. L. *Sci. Adv.* **3**, e1700782 (2017).
8. Stegmann, P., Daioglou, V., Londo, M. & Junginger, M. *MethodsX* **9**, 101666 (2022).

The authors declare competing interests. See go.nature.com/3apolxc for details.