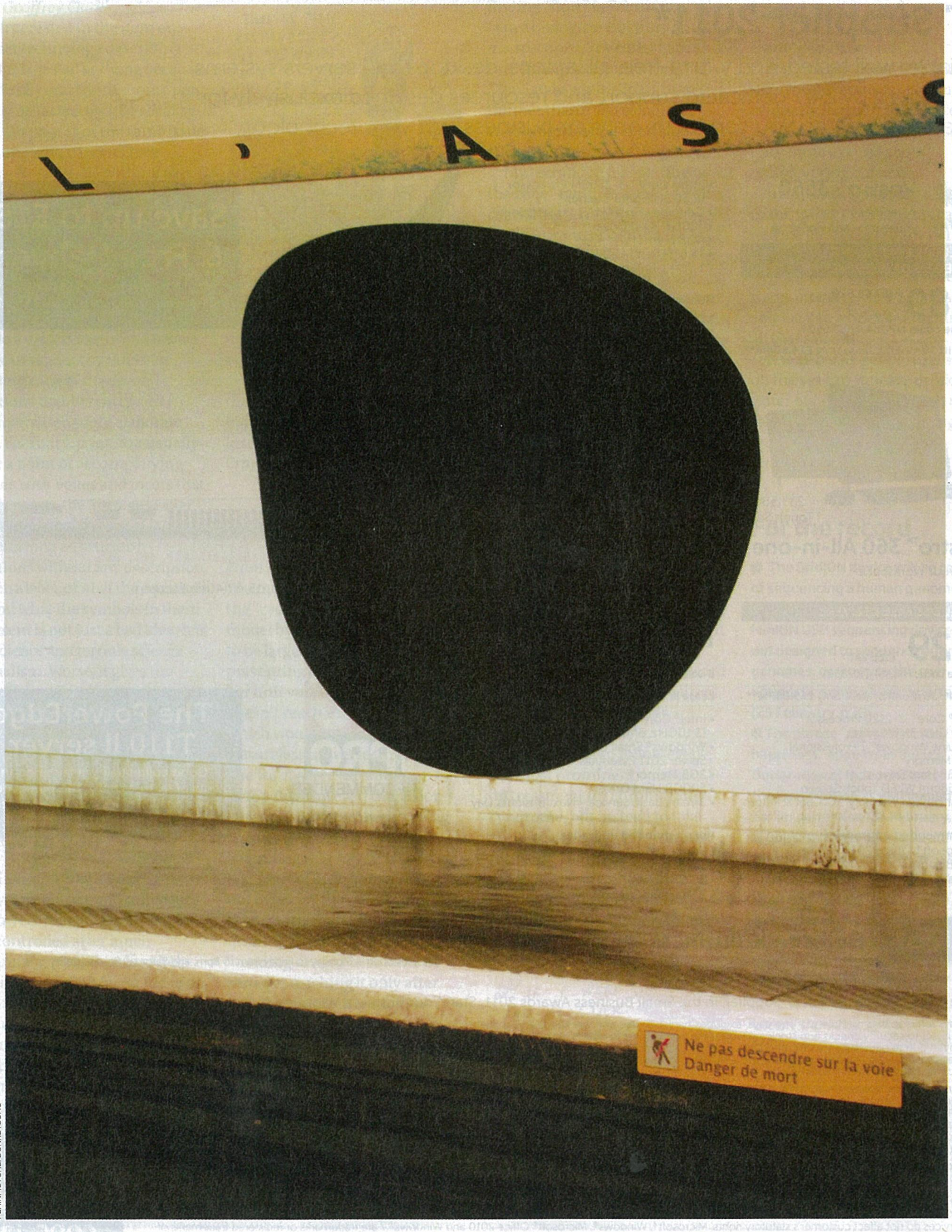


PLAINPICTURE/DONKEYSOHO

If intergalactic travel is on your wish list we have plenty of wormholes to choose from, says **Marcus Chown**

Return ticket to Andromeda, please

IT IS not every day that a piece of science fiction takes a step closer to nuts-and-bolts reality. But that is what seems to be happening to wormholes. Enter one of these tunnels through space-time, and a few short steps later you may emerge near Pluto or even in the Andromeda galaxy millions of light years away.

You probably won't be surprised to learn that no one has yet come close to constructing such a wormhole. One reason is that they are notoriously unstable. Even on paper, they have a tendency to snap shut in the blink of an eye unless they are propped open by an exotic form of matter with negative energy, whose existence is itself in doubt.

Now, all that has changed. A team of physicists from Germany and Greece has shown that building wormholes may be possible without any input from negative energy at all. "You don't even need normal matter with positive energy," says Burkhard Kleihaus of the University of Oldenburg in Germany. "Wormholes can be propped open with nothing."

The findings raise the tantilising possibility that we might finally be able to detect a wormhole in space. Civilisations far more advanced than ours may already be shuttling back and forth through a galactic-wide subway system constructed from wormholes. And eventually we might even be able to use them ourselves as portals to other universes.

Wormholes first emerged in Einstein's general theory of relativity, which famously shows that gravity is nothing more than the hidden warping of space-time by energy, usually the mass-energy of stars and galaxies. Soon after Einstein published his equations in 1916, Austrian physicist Ludwig Flamm discovered that they also predicted conduits through space and time.

But it was Einstein himself who made detailed investigations of wormholes with Nathan Rosen. In 1935, they concocted one consisting of two black holes, connected by a tunnel through space-time. Travelling through their wormhole was only possible if the black holes at either end were of a special kind. A conventional black hole has such a

"Wormholes are well and truly on the menu of astrophysical possibilities in any post-Einstein world"

powerful gravitational field that material sucked in can never escape once it has crossed what is called the event horizon. The black holes at the end of an Einstein-Rosen wormhole would be unencumbered by such points of no return.

Einstein and Rosen's wormholes seemed a mere curiosity for another reason: their destination was inconceivable. The only connection the wormholes offered from our universe was to a region of space in a parallel universe, perhaps with its own stars, galaxies and planets. While today's theorists are comfortable with the idea of our universe being just one of many, in Einstein and Rosen's day such a multiverse was unthinkable.

Fortunately, it turned out that general relativity permitted the existence of another type of wormhole. In 1955, American physicist John Wheeler showed that it was possible to connect two regions of space in our universe, which would be far more useful for fast intergalactic travel. He coined the catchy name wormhole to add to black holes, which he can also take credit for.

The trouble is the wormholes of Wheeler and Einstein and Rosen all have the same flaw. They are unstable. Send even a single photon of light zooming through and it instantly triggers the formation of an event horizon, which effectively snaps shut the wormhole.

Bizarrely, it is the American planetary astronomer Carl Sagan who is credited with moving the field on. In his science fiction novel, *Contact*, he needed a quick and scientifically sound method of galactic transport for his heroine – played by Jodie Foster in the movie. Sagan asked theorist Kip Thorne at the California Institute of Technology in Pasadena for help, and Thorne realised a wormhole would do the trick. In 1987, he and his graduate students Michael Morris and Uri Yertsever worked out the recipe to create a traversable wormhole. It turned out that the mouths could be kept open by hypothetical material possessing a negative energy. Given enough negative energy, such a material has a repulsive form of gravity, which physically pushes open the wormhole mouth.

Negative energy is not such a ridiculous idea. Imagine two parallel metal plates sitting in a vacuum. If you place them close together the vacuum between them has negative › energy – that is, less energy than the vacuum outside. This is because a normal vacuum is like a roiling sea of waves, and the waves that are too big to fit between the plates are naturally excluded. This leaves less energy inside the plates than outside.

Unfortunately, this kind of negative energy exists in quantities far too feeble to prop open a wormhole mouth. Not only that but a Thorne-Morris-Yertsever wormhole that is big enough for someone to crawl through requires a tremendous amount of energy – equivalent to the energy pumped out in a year by an appreciable fraction of the stars in the galaxy.

Back to the drawing board then? Not quite. There may be a way to bypass those difficulties. All the wormholes envisioned until recently assume that Einstein's theory of gravity is correct. In fact, this is unlikely to be the case. For a start, the theory breaks down at the heart of a black hole, as well as at the beginning of time in the big bang. Also, quantum theory, which describes the microscopic world of atoms, is incompatible with general relativity. Since quantum theory is supremely successful – explaining everything from why the ground is solid to how the sun shines – many researchers believe that Einstein's theory of gravity must be an approximation of a deeper theory.

"Even the supermassive black hole at the centre of our Milky Way might be a wormhole"

A world beyond Einstein

A hint of what a deeper theory would look like came in 1921. Theodor Kaluza and Oskar Klein were inspired by Einstein's success in showing that gravity is the curvature of a four-dimensional sheet made by melding together the three dimensions of space with time. They went on to show that both gravity and the electromagnetic force could be explained by the curvature of a five-dimensional space-time. More recently, string theorists claim that all four fundamental forces might be explained by warping 10-dimensional space-time.

Crucially, when space-time has more than four dimensions, the powerful theorems which forbid a wormhole unless it is propped open by negative energy may not apply. In 2002, Kirill Bronnikov at the Centre of Gravitation and Fundamental Metrology in Moscow, Russia, and Sung-Won Kim at Ewha Womans University in Seoul, South Korea, raised the possibility of a wormhole existing without exotic matter (*Physical Review D*, vol 67, p 064027). They uncovered a wealth of wormhole solutions in one of the popular versions of brane-world gravity, which describes our world as a 4D island or "brane" floating in higher dimensions. "No phantom matter is required, and the wormholes can have an arbitrary size," says Bronnikov.

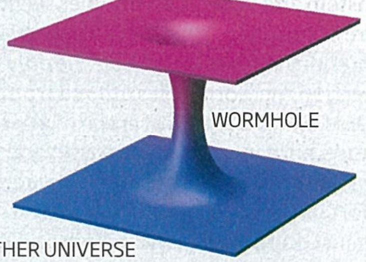
Such higher-dimensional theories of gravity such as string theory are notoriously difficult to work with, however. Enter Kleihaus and his colleagues Jutta Kunz, also at the University of Oldenburg, and Panagiota Kanti of the University of Ioannina in Greece. They have recently been exploring hypothetical but plausible extensions of Einstein's theory of gravity that are easier to handle. The simplest of these theoretical frameworks goes by the unwieldy name of dilatonic Einstein-Gauss-Bonnet theory, or the much snappier DEGB theory.

If the extra dimensions of higher dimensional theories are rolled up very small, or "compactified", that would explain why we do not experience them directly. The process of compactifying the extra six dimensions of string theory creates several new force fields, such as the so-called dilaton field. In the same way that general relativity describes gravity as the curvature of space, gravity in DEGB theory depends on the curvature plus the curvature raised to a higher power.

A tale of two wormholes

In general relativity, wormholes permit travel between different places in our universe, but they require matter with negative energy

A minor modification to general relativity allows wormholes between our universe and another to exist without the need for exotic matter



Using this extra term in the gravitational equations, Kleihaus and his colleagues have discovered a solution for a wormhole. It needs no stuff made of negative energy to prop it open, or, indeed, any matter at all (*Physical Review Letters*, vol 107, p 271101).

Other researchers welcome the findings, albeit with caution. "I think this is quite important and makes the idea of traversable wormholes more likely," says Aurélien Barrau of the Laboratory of Subatomic Physics and Cosmology in Grenoble, France. "Even if no exotic matter is required, this still relies on very speculative ideas."

Taken together with Bronnikov and Kim's work, it seems that wormholes are well and truly on the menu of astrophysical possibilities in any post-Einstein world. Excitingly, the wormholes Kleihaus's team envisage are of the type that connects two regions in separate universes. What seemed a mere exotic curiosity in Einstein's day is not the case now. The advent of string theory has led some theorists to speculate that our universe with its three dimensions of space is a 3-brane floating in a higher-dimensional space. But out there, there could be other universes that are 4-branes, 5-branes and so on. Suddenly a wormhole that connects different universes is an exciting prospect.

Could such wormholes exist out there in space? Quite possibly. Wheeler suggested that quantum fluctuations would transform the gently undulating fabric of space-time at close range into a seething mass of complex shapes, known as quantum foam. According to this picture, exceedingly small wormholes with different topologies would appear and disappear in a flash.

Yet there is a natural process that could already have magnified these wormholes, making them large enough to travel through today. Inflation, as we call it, is widely thought

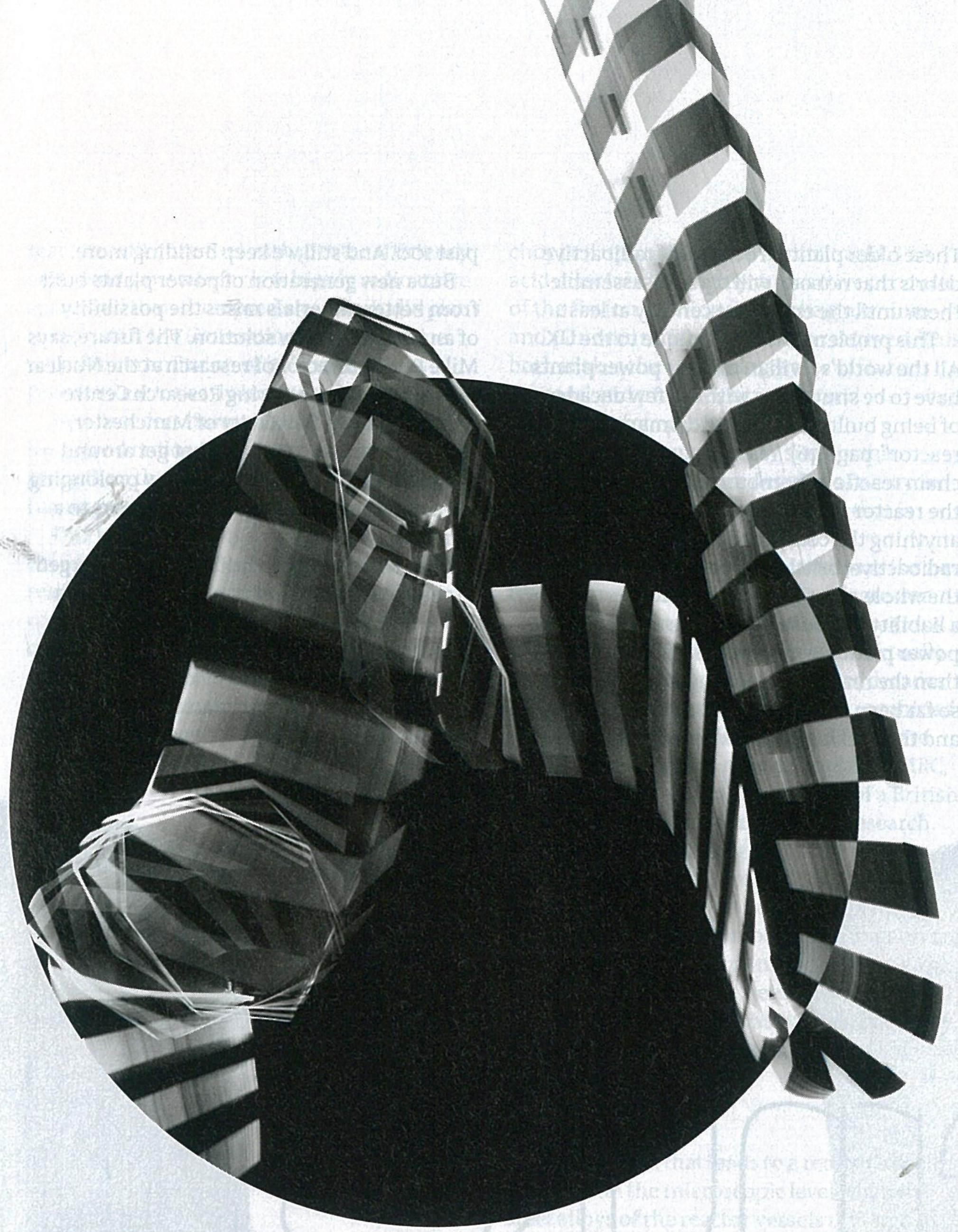


PHOTO: LIGHT PAINTING BY PATRICK ROCHON

"A civilisation more advanced than ours may already be riding an extraterrestrial subway system"

to have operated in the first split-second of the universe's existence, prompting it to balloon enormously and at breathtaking speed. "At the same time, it could have ballooned the tiny wormholes that make up the sub-microscopic fabric of space," says Kleihaus.

He and his colleagues have thoroughly investigated the properties of their wormhole inflated this way (arxiv.org/abs/1111.4049). For it to be traversable, the differences in gravity across a body travelling through the wormhole must be small enough to keep the body intact. The good news, says Kleihaus, is that the photons and subatomic particles can easily travel through. The bad news is that for a massive human being to travel through unscathed by gravity, the wormhole mouth needs to curve very gently and this means it must be tens to hundreds of light years across.

If this seems a bit excessive, consider the upside. According to Kleihaus, the scale of such wormholes presents us with a golden opportunity to spot them out in space. As a telescope scans across the star field and hits a wormhole it would see an abrupt change in the view. "The wormhole mouth, after all, is a window on another universe," says Kleihaus.

In general, though, even enormous wormholes will be difficult to spot. When hidden by dust and gas and stars, they look very similar to black holes. It is even possible that Sagittarius A*, the supermassive black hole at the centre of our Milky Way, could be a wormhole. One way to be sure, says Kleihaus, would be to study matter falling in.

Observations show that gas swirling around a black hole forms a disc of matter so hot it emits X-rays, and we expect the same at the mouths of wormholes. No one has yet built a telescope of sufficiently high resolution to image the very core of a black hole, though astronomers are constructing one capable of snapping Sagittarius A* (*New Scientist*, 4 February, p 27). If Sagittarius A* is indeed a black hole, then we would expect the X-rays to cut off suddenly as the gas crosses the event horizon never to be seen again. On the other hand, if it is the entrance to a wormhole, then we would still see the X-rays because wormholes do not have event horizons.

Kleihaus and his colleagues are also hoping astronomers will help them to deduce what other signatures of wormholes might look like. One possibility is that, if a wormhole passes between a distant star and the Earth, its gravity will distort, or "gravitationally lens", the light of the distant star in a distinctive way.

While the wormhole solution found so far in DEGB theory connects our universe to another, it is still possible that other solutions exist that connect different parts of our universe. Kleihaus and his colleagues intend to investigate this possibility. Such a wormhole would open up the prospect of an extraterrestrial subway system.

Before you start saving for a season ticket, though, be warned that the Milky Way may not be a destination on the subway map. That's because our galaxy's stars are crowded together within a few light years of each other. While this doesn't prevent the existence of a wormhole with a mouth tens of light years across, it makes it hard to position it so that star systems don't accidentally fall in. Fallen stars would surely disrupt the timetable and so users might avoid our galaxy altogether.

There is no such problem, of course, in the emptiness between galaxies. Perhaps, at this very moment, there is an intergalactic subway system connecting the region just beyond the Milky Way to Andromeda, the Large Magellanic Cloud or the Whirlpool galaxy. It would sure beat taking the subway in your nearest town. ■

Marcus Chown has explored the comic possibilities of wormholes in his children's book, *Felicity Frobisher and the Three-Headed Aldebaran Dust Devil* (Faber & Faber, 2008)