Wormholes, Warp-drives, and other Weirdness

Matt Visser
Physics Department
Washington University
Saint Louis
USA

U Maryland

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Abstract:

Over the last decade or so it has become increasingly clear that the interface between quantum physics and Einstein's gravity (general relativity) seems to lead to (or at least permit) a large number of very strange theoretical constructs.

The fringes of general relativity almost seem to be infested with wormholes, warp-drives, and even time-machines.

While it is clear that we will not be able to build such objects in the foreseeable future—the technological difficulties are immense—they provide very useful gedanken-experiments for sharpening our ideas of what the ultimate quantum theory of gravity should look like.

Topics to be discussed:

Morris–Thorne traversable wormholes.

Exotic matter (negative energy).

Alcubierre's warp drive.

Time machines.

Temporal paradoxes.

Hawking's chronology protection conjecture.

Classical violations of the Energy Conditions.

Strategy:

[1] Decide on your definition of a wormhole/ warp-drive/ time machine.

What does the spacetime geometry look like?

[2] Given the geometry, use the Einstein equations to calculate the distribution of matter required to set up this geometry.

[3] Ask: Is this distribution of matter physically reasonable?

Does it violate any basic rules of physics?

Is the construction of wormholes/ warp-drives/ time machines merely a problem of technology, or is it in violation of fundamental physical principles?

What is a wormhole?

Morris–Thorne traversable wormholes:

- Q: What would you have to do to build a wormhole that you could safely stuff a human through?

- A: Nothing too drastic: you just need to some "negative energy".

- Quantum effects are potentially important.

- Warning: We know how to get small amounts of "negative energy"; We don't know if it is possible to get large quantities of "negative energy".

Traversable wormhole geometry:

An example:

Take the geometry

$$ds^2 = -dt^2 + \left[1 + \frac{GM}{2r}\right]^4 \left(dx^2 + dy^2 + dz^2\right).$$

(This is Schwarzschild geometry in isotropic coordinates; with $g_{tt} \to -1$ to get rid of the event horizon.)

This solves the Einstein equations with a source

$$T_{\mu\nu} = -\nabla_\mu \phi \, \nabla_\nu \phi.$$

(Which corresponds to a massless scalar field with the wrong sign for the stress–energy tensor.)

Homer G. Ellis:
Drainholes and reversed polarity gravity.

A brief history of wormhole physics:

- 1916:Flamm; Phys Z.

- 1935: Einstein—Rosen;
  PR 48 (1935) 73–77.

  "These solutions involve the mathematical representation of physical space by a space of two identical sheets, a particle being represented by a 'bridge' connecting these sheets."

- This is the Einstein–Rosen bridge.

- Do not attempt to cross an Einstein–Rosen bridge — You will die.

- 1955: Wheeler; PR 97 (1955) 511–536.

Wheeler discusses a special type of *“geon”* that possesses two *“tunnel mouths”*.

— First diagram of a wormhole.

> “One’s interest in following geon theory down into the quantum domain will depend on one’s considered view of the relationship between very small geons and elementary particles.”

- 1957: Misner–Wheeler; AP(NY) 2 (1957) 525–603.

“There is a net flux of lines of force through what topologists would call a handle of the multiply–connected space and what physicists might perhaps be excused for more vividly terming a ‘wormhole’.”

— First use of the word “wormhole”.

“On the atomic scale the metric appears flat, as does the ocean to an aviator far above. The closer the approach, the greater the degree of irregularity. Finally, at distances of the order of ℓ_P, the fluctuations in the typical metric component, $g_{\mu\nu}$, become of the same order as the $g_{\mu\nu}$ themselves.”

- 1957: Wheeler;
  AP(NY) 2 (1957) 604–614.

  "Space 'resonates' between one foam-like structure and another."

  "*Spacetime foam*"

- 1960's: "quantum higgledy–piggledy".

- 1974: J. A. Wyler;
  GRG 5 (1974) 175–182.
  Rasputin, science, and the transmogrification of destiny.

Renaissance:

- 1988: Morris–Thorne;
  AJP 56 (1988) 935–412.
  - traversable wormholes.
  - time travel.
- 1989: Novikov
  - time machines.
- 1989: Visser
  - portals.
  - stability.

- 1990: Frolov–Novikov
  - time machines.
  - perpetual motion.

- 1990's: Morris — Thorne — Yurtsever — Hawking — Novikov — Frolov — Kim — Klinkhammer — Lyutikov — Ford — Roman — Visser — and many others...
  - chronology protection.
  - quantum effects.

- 1990's:
  Wormholes enter the popular culture
  — ST:tng, ST:ds9, ST:voyager —
  — Sliders, Stargate —

Averaged Null Energy Condition violations:

It is a **theorem** that spacetimes containing traversable wormholes always violate the averaged null energy condition: Friedmann–Schleich–Witt.

In fact there will always be null energy condition violations at or near the throat.

(This is a fancy way of saying that you need to have some effectively "negative mass" at or near the throat to keep the wormhole throat open.)

Static spherical symmetry: Morris–Thorne.
Dynamic asymmetric: Hochberg–Visser.

There are quite a few **claims** that energy condition violations can be avoided.

Wormholes without ANEC violation?

Most of these claims are simply wrong.

Some of these claims are just semantic games.

[Divide the total stress-energy into “weird stuff” plus “normal stuff”, push all the energy condition violations into the “weird stuff” so that the “normal stuff” does not violate the energy conditions.]

Traversable wormholes **violate the averaged (and unaveraged) null energy condition.**

How big a violation?

Typically, near the throat, you need:

$$(mass \text{ @ } throat) = -\frac{(radius)\ c^2}{G}.$$

For $(radius) = 1$ metre,
$(mass \text{ @ } throat) = -1$ Jupiter mass!

Total mass might still be close to zero
(in principle, either positive or negative).

Whether or not large "mass separation" is
possible (even in principle) is far from clear.

The Alcubierre Warp Drive:

The warp drive:
Hyper-fast travel in general relativity,
by Miguel Alcubierre,
Classical and Quantum Gravity,
11 (1995) L73–L77.

In general relativity, nothing can *locally* exceed the speed of light.

But if the space-time geometry is suitably arranged, you can think of the light-cones as "tipping over" with respect to some flat background geometry, so that *globally* objects can "effectively" travel faster-than-light [with respect to the background geometry].

Warp Drive Geometry:

Pick the metric (i.e. distance function):

$$ds^2 = -dt^2 + (dx - v_s\, f(r)\, dt)^2 + dy^2 + dz^2.$$

$$ds^2 = -dt^2(1 - v_s^2\, f(r)^2) - 2v_s\, f(r)\, dx\, dt$$
$$+dx^2 + dy^2 + dz^2.$$

The metric of 3D space is flat, all the complications are hiding in the space-time cross terms.
v_s is the speed of the warp bubble.
$f(r)$ describes the shape of the warp bubble, with

$$r(x, y, z, t) = \sqrt{(x - v_s\, t)^2 + y^2 + z^2}$$

and

$$f(0) = 1; \qquad\qquad f(\infty) = 0.$$

Warp Drive stress–energy:

Use the Einstein equations to calculate the stress-energy.

Bad news: the energy density is negative!

$$\rho = -\frac{1}{8\pi G} \frac{v_s^2 (y^2 + z^2)}{4\left[(x - v_s\, t)^2 + y^2 + z^2\right]} \left(\frac{df}{dr}\right)^2 .$$

Other parts of the stress-energy are worse.

The deep question is: Is this negative energy density enough to tell you cannot, not ever, build a warp drive?

The answer is not obvious...

(Surprise?)

Problem:

Traversable wormholes imply time machines.

Q: What is a time machine?

A: Any closed timelike curve (CTC) — not necessarily a geodesic.

Given a traversable wormhole, it *appears* to be very easy to build a time machine.

It is so easy that it *seems* that the creation of a time machine might be the generic fate of a traversable wormhole.

In fact, classical general relativity is pretty much infested with time machines...

(diseased time machines to be sure..)

How to build a time machine?

1. Get your hands on a traversable wormhole.

2. Induce a time shift between the two mouths.

   - SR time dilation — rectilinear motion.
   - SR time dilation — circular motion.
   - GR time dilation — gravitational redshift.

3. Bring the two mouths together.

Whatever you do:
— don't mention the twin paradox —
It only puts the lunatic fringe into an excited state.

Problem: Time machines imply paradoxes.

Two classes of paradox —

- consistency paradoxes.
- bootstrap paradoxes.

Examples —

- All you zombies.
- By his bootstraps.
- The technicolor time machine.

Responses:

There are *many* ways of dealing with the paradoxes.

1. The radical rewrite conjecture.
   "all hell breaks loose"

2. The Novikov consistency conjecture.
   "suffer not an inconsistency to exist"

3. The Hawking chronology protection conjecture.
   "suffer not a time machine to exist"

4. The boring physics conjecture.
   "forget all this nonsense"

The radical rewrite conjecture:

Rewrite all of physics from the ground up — let the universe have multiple timelines, with time travel effects switching the universe from one timeline to another.

Rewriting physics is a very painful task — not to be undertaken lightly. Especially since there is NO experimental evidence...

One begins to sound like a refugee from a bad sci–fi convention...

> "Whenever one attempts to change history, the resulting temporal anomaly emits a non–Hausdorff wavefront which sweeps out and splits the universe into two separate histories..."

For a real mess; add quantum physics...

The Novikov consistency conjecture:

Classical — There is only one universe.
The universe *must* be consistent no matter what...

"You can't change recorded history".

Complicated situations lead to a rather unsatisfying "consistency conspiracy".

Quantum — Try to derive consistency from some assumed microphysics for quantum gravity.

Inconsistent histories interfere destructively?

In the presence of time travel, certain low probability events become virtual certainties.

Quantum effects blur the line between multiple timelines and consistency constraints...

Hawking's chronology protection conjecture:

Quotes from Stephen Hawking: (PRD)

> "The laws of physics do not allow the appearance of closed timelike curves."

> "It seems that there is a Chronology Protection Agency which prevents the appearance of closed timelike curves and so makes the universe safe for historians."

> "There is also strong experimental evidence in favour of the conjecture — from the fact that we have not been invaded by hordes of tourists from the future."

The Physics of chronology protection:

Physically the conjecture is based on the observation that there are nasty singularities in the renormalized stress–energy tensor as one gets close to forming a time machine...

That is — once quantum effects are included, the energy required to build a time machine is infinite.

— The "chronology horizon" is thoroughly unpleasant place; our current theories are unreliable.

[Two-point functions are not of Hadamard form.]

— The "chronology horizon" always hides behind a "reliability horizon".

The boring physics conjecture:

Just forget about all of these nasty messes —

- Abolish traversable wormholes;
- Abolish complicated topology;
- Enforce strong cosmic censorship;
- and be done with it...

After all, what's the experimental evidence?

Time for a reality check!

Unfortunately; Reality bites:

Classical: In classical general relativity the various energy conditions are used to prove lots of lovely general theorems...

Quantum: Everyone who thought about it expected the various energy conditions to eventually break down once one reaches the Planck slop...

Surprise 1: The various energy conditions already fail miserably in **semi-classical quantum gravity**.

The failures occur at first order in $\hbar$, long before one reaches the Planck slop...

The failures are widespread, albeit small...

Surprise 2: The various energy conditions also fail miserably in some quite reasonable looking **classical systems**.

Quantum violations of the energy conditions:

- 2-particle Fock states. (NEC+)

- Casimir vacuum. (NEC+)
  [DeWitt; Einstein Centenary Survey]

- Hawking radiation. (NEC+)

- Squeezed vacuum. (WEC+DEC)
  [Morris–Thorne]

- Conformal anomaly (NEC+)
  [Visser, PLB 349 (1995) 443–447; gr-qc/9409043].

- Gravitational vacuum polarization (NEC+)
  [Visser, gr-qc/9604007; 9604008; 9604009; 9703001].

Classical violations of the energy conditions:

- Cosmological inflation. (SEC)
  [Minimally coupled massive scalar]
  [Theory only, for now]

- Galaxy formation: $0 < z < 10$. (SEC)
  [Visser, Science 276 (4 April 1997) 88]
  [Observation: accelerating universe]

- Non-minimally coupled scalar (NEC+)
  massive/massless
  [Wald–Flanagan, gr-qc/9602052, PRD].

- Massless conformally coupled scalar (NEC+)
  QFT: new improved energy-momentum
  [Barceló–Visser, gr-qc/9908029, PLB]

Tolman wormhole:

Q: What are the *minimal* conditions for a “bounce”?

Definition: Tolman wormhole $\equiv$ “bounce”.

A: Perform a model-independent analysis of the geometry near a bounce, along the lines of the Morris–Thorne analysis for traversable wormholes.

Details:
gr-qc/9810023, PLB455 (1999) 90-95
[Molina-París, Visser]
gr-qc/9810029, PRD59 (1999) 044011
[Hochberg, Molina-París, Visser]

Flare-out at the bounce $\Rightarrow$ SEC violated at or near the bounce.

Notes:

SEC violations are a *necessary* but not *sufficient* condition for a "bounce".

You do not *need* to violate NEC, WEC, or DEC to get a "bounce".

If you believe inflation you have already abandoned the SEC anyway.

Inflation will not *guarantee* a bounce, but it opens the door.

New improved stress tensor plus gravity:

Q: What happens if you take a massless conformally coupled scalar field and add Einstein gravity? (Static, spherically symmetric.)

This looks an absurdly easy problem, but the result is somewhat of a surprise.

A: There is a three-parameter class of exact solutions (total mass, scalar charge, scalar field at infinity).

Special cases:
(1) Schwarzschild/ anti-Schwarzschild.
(2) Naked singularities.
(3) Naked singularities hiding behind wormhole throats. (Not really "traversable".)
(4) Traversable wormholes with two asymptotically flat regions.

Details: gr-qc/9908029, Barceló–Visser, PLB.

Specific Implications:

Don't focus on the specific technical details. (Naked singularities, traversable wormholes). The main points are these:

- Classical arbitrarily large violations of the NEC and ANEC arise in this otherwise very reasonable classical system.

- Conformally coupled scalars are from a QFT perspective the preferred choice — corresponding to the new improved stress-energy tensor.
  (Conformal coupling is a IR fixed point of the RG.)

- It's the fact that you get significant NEC violation in such a simple physical system that's worrying — the fact that this NEC violation is big enough to support traversable wormholes is a bonus.

General Implications:

- Traversable wormholes almost begin to look physically reasonable.
- Tolman wormholes almost begin to look physically reasonable.
- Warp drives almost begin to look physically reasonable.
- This opens up a whole mess of weird possibilities...
- Time travel looks downright unpleasant.
  — *and* — there are calculations to back this up.
  — *and* — there is experimental "evidence".
- No new physics is used!

Conclusions:

Desperately seeking quantum gravity:

- **Bottom up approach** — We are pushing general relativity to its limits (and beyond?) hoping that it will "break" in an interesting manner.

- **Top down approach** — Whatever the "true" theory of quantum gravity is, at "low" energy any acceptable theory of quantum gravity must begin to address the issues raised in this colloquium.

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