



Accounting for exotic matter and the extreme radial tension in Morris–Thorne wormholes of embedding class one

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Abstract The embedding of a curved spacetime in a higher-dimensional flat spacetime has continued to be a topic of interest in the general theory of relativity, as exemplified by the induced-matter theory. This paper deals with spacetimes of embedding class one, i.e., spacetimes that can be embedded in a five-dimensional flat spacetime. Einstein's theory allows the fifth dimension to be either spacelike or timelike. By assuming the latter, this paper addresses two fundamental issues concerning Morris–Thorne wormholes, the origin of exotic matter and the frequently inexplicable enormous radial tension at the throat.

1 Introduction

Wormholes are handles or tunnels in spacetime connecting widely separated regions of our Universe or different universes in a multiverse. Apart from some forerunners, macroscopic traversable wormholes were first studied in detail by Morris and Thorne [1] in 1988. They had proposed the following static and spherically symmetric line element for a wormhole spacetime:

$$ds^2 = -e^{\nu(r)} dt^2 + e^{\lambda(r)} dr^2 + r^2(d\theta^2 + \sin^2\theta d\phi^2), \quad (1)$$

where

$$e^{\lambda(r)} = \frac{1}{1 - \frac{b(r)}{r}}. \quad (2)$$

(We are using units in which $c = G = 1$; the only exceptions are Eqs. (8) and (9) since these involve numerical calculations.) Here $v = v(r)$ is called the *redshift function*, which must be everywhere finite to prevent an event horizon. The function $b = b(r)$ is called the *shape function* since it determines the spatial shape of the wormhole when viewed, for

example, in an embedding diagram [1]. The spherical surface $r = r_0$ is called the *throat* of the wormhole, where $b(r_0) = r_0$. The shape function must also meet the following requirements: $b'(r_0) < 1$, called the *flare-out condition*, and $b(r) < r$ for $r > r_0$. A final requirement is asymptotic flatness: $\lim_{r \rightarrow \infty} v(r) = 0$ and $\lim_{r \rightarrow \infty} b(r)/r = 0$.

The flare-out condition can only be met by violating the null energy condition (NEC), $T_{\alpha\beta}k^\alpha k^\beta \geq 0$, for all null vectors k^α , where $T_{\alpha\beta}$ is the energy-momentum tensor. Matter that violates the NEC is called “exotic” in Ref. [1]. For the outgoing null vector $(1, 1, 0, 0)$, the violation becomes

$$T_{\alpha\beta}k^\alpha k^\beta = \rho + p_r < 0. \quad (3)$$

Here $T'_t = -\rho$ is the energy density, $T'_r = p_r$ is the radial pressure, and $T'_\theta = T'_\phi = p_r$ is the lateral (transverse) pressure.

Before continuing, let us list the Einstein field equations:

$$8\pi\rho = e^{-\lambda} \left[\frac{\lambda'}{r} - \frac{1}{r^2} \right] + \frac{1}{r^2}, \quad (4)$$

$$8\pi p_r = e^{-\lambda} \left[\frac{1}{r^2} + \frac{v'}{r} \right] - \frac{1}{r^2}, \quad (5)$$

and

$$8\pi p_\theta = \frac{1}{2} e^{-\lambda} \left[\frac{1}{2} (v')^2 + v'' - \frac{1}{2} \lambda' v' + \frac{1}{r} (v' - \lambda') \right]. \quad (6)$$

In this paper, we are going to look at two particular aspects of wormhole physics, the origin of exotic matter and the enormous radial tension at any throat of moderate size.

First we need to recall that exotic matter by itself does not pose a conceptual problem, as illustrated by the Casimir effect [1]: exotic matter could be made in the laboratory. The question is whether there could ever be enough exotic matter to sustain a macroscopic traversable wormhole. In fact, some researchers consider any such wormhole solutions unphysical. It should also be emphasized that Hochberg and Visser

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