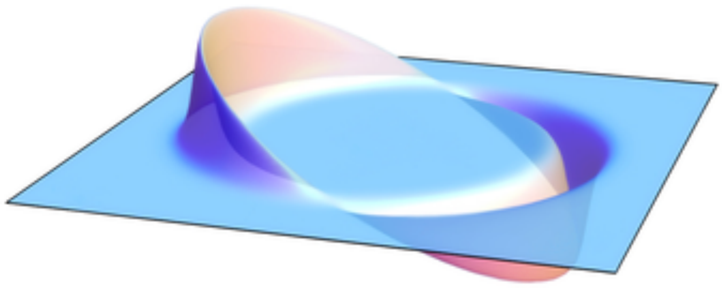
Alcubierre drive



The **Alcubierre drive** (or ***Alcubierre metric*** see: Metric tensor) is a speculative idea based on a valid solution of the Einstein field equations as proposed by Miguel Alcubierre by which a spacecraft might achieve faster-than-light travel, making travel to other stars a possibility. Rather than exceeding the speed of light within its local frame of reference, the ship would traverse distances by contracting space in front of it and expanding space behind it.

History

In 1994 Alcubierre proposed a way of changing the geometry of space by creating a wave which would cause the fabric of space ahead of a spacecraft to contract and the space behind it to expand.[1] The ship would then ride this wave inside a region of flat space known as a *warp bubble*, and would not move within this bubble, but instead be carried along as the region itself moves as a consequence of the actions of the drive. If this is so, conventional relativistic effects such as *time dilation* would not apply in the way they would in the case of a ship moving at a very great velocity through flat spacetime, relative to other objects. This method of propulsion would not involve objects in motion at speeds faster than light with respect to the contents of the *warp-bubble*; that is, a light beam within the *warp-bubble* would still always move faster than the ship. Thus the mathematical formulation of the *Alcubierre metric* does not contradict the conventional claim that the laws of relativity do not allow a slower-than-light object to accelerate to faster-than-light speeds. The Alcubierre drive, however, remains a hypothetical concept with seemingly insuperable problems: The amount of energy required is unobtainably large, there is no method to create a warp bubble in a region that does not already contain one, and there is no method to move from the warp-bubble once having arrived at an intended destination.

Alcubierre metric

The Alcubierre metric defines the warp drive spacetime. This is a Lorentzian manifold which, if interpreted in the context of general relativity, allows a *warp bubble* to appear in previously flat spacetime and move off at effectively superluminal speed. Inhabitants of the bubble feel no inertial effects. The object(s) within the bubble are not moving (locally) faster than light, instead, the space around them shifts so that the object(s) arrives at its destination faster than light would in normal space.[2]

Alcubierre chose a specific form for the function *f*, but other choices[*which?*] give a simpler spacetime exhibiting the desired "warp drive" effects more clearly and simply.

Mathematics of the Alcubierre drive

Using the ADM formalism of general relativity, the spacetime is described by a foliation of space-like hypersurfaces of constant coordinate time *t*. The general form of the metric described within the context of this formalism is:

$$ds^2 = -\left(\alpha^2 - \beta_i\beta^i\right)dt^2 + 2\beta_i\,dx^i\,dt + \gamma_{ij}\,dx^i\,dx^j$$ where

α is the lapse function that gives the interval of proper time between nearby hypersurfaces,
β^i is the shift vector that relates the spatial coordinate systems on different hypersurfaces
γ_{ij} is a positive definite metric on each of the hypersurfaces.

The particular form that Alcubierre studied [1] is defined by:

$$\alpha = 1 \quad \beta^x = -v_s(t)f\left(r_s(t)\right), \quad \beta^y = \beta^z = 0 \quad \gamma_{ij} = \delta_{ij}$$

where

$$v_s(t) = \frac{dx_s(t)}{dt},$$
$$r_s(t) = \sqrt{(x - x_s(t))^2 + y^2 + z^2}$$

and

$$f(r_s) = \frac{\tanh(\sigma(r_s + R)) - \tanh(\sigma(r_s - R))}{2\tanh(\sigma R)}$$ $R > 0$ $\sigma > 0$ with and arbitrary parameters. Alcubierre's specific form of the metric can thus be written;

$$ds^2 = \left(v_s(t)^2 f(r_s(t))^2 - 1\right)\, dt^2 - 2v_s(t) f(r_s(t))\, dx\, dt + dx^2 + dy^2 + dz^2$$

With this particular form of the metric, it can be shown that the energy density measured by observers whose 4-velocity is normal to the hypersurfaces is given by

$$-\frac{c^4}{8\pi G}\frac{v_s^2(y^2+z^2)}{4g^2 r_s^2}\left(\frac{df}{dr_s}\right)^2$$

where g is the determinant of the metric tensor.

Thus, as the energy density is negative, one needs exotic matter to travel faster than the speed of light.[1] The existence of exotic matter is not theoretically ruled out; however, generating enough exotic matter and sustaining it to perform feats such as faster-than-light travel (and also to keep open the 'throat' of a wormhole) is thought to be impractical. Low has argued that within the context of general relativity, it is impossible to construct a warp drive in the absence of exotic matter.[3] It is generally believed that a consistent theory of quantum gravity will resolve such issues once and for all.

Physics

For those familiar with the effects of special relativity, such as Lorentz contraction and time dilation, the Alcubierre metric has some apparently peculiar aspects. In particular, Alcubierre has shown that even when the ship is accelerating, it travels on a free-fall geodesic. In other words, a ship using the warp to accelerate and decelerate is always in free fall, and the crew would experience no accelerational g-forces. Enormous tidal forces would be present near the edges of the flat-space volume because of the large space curvature there, but by suitable specification of the metric, these would be made very small within the volume occupied by the ship.[1]

The original warp drive metric, and simple variants of it, happen to have the *ADM form* which is often used in discussing the initial-value formulation of general relativity. This may explain the widespread misconception that this spacetime is a *solution* of the field equation of general relativity. Metrics in ADM form are *adapted* to a certain family of inertial observers, but these observers are not really physically distinguished from other such families. Alcubierre interpreted his "warp bubble" in terms of a contraction of "space" ahead of the bubble and an expansion behind. But this interpretation might be misleading,[4] since the contraction and expansion actually refers to the relative motion of nearby members of the family of ADM observers.

In general relativity, one often first specifies a plausible distribution of matter and energy, and then finds the geometry of the spacetime associated with it; but it is also possible to run the Einstein field equations in the other direction, first specifying a metric and then finding the energy-momentum tensor associated with it, and this is what Alcubierre did in building his metric. This practice means that the solution can violate various energy conditions and require exotic matter. The need for exotic matter leads to questions about whether it is actually possible to find a way to distribute the matter in an initial spacetime which lacks a "warp bubble" in such a way that the bubble will be created at a later time. Yet another problem is that, according to Serguei Krasnikov,[5] it would be impossible to generate the bubble without being able to force the exotic matter to move at *locally* FTL speeds, which would require the existence of tachyons. Some methods have been suggested which would avoid the problem of tachyonic motion, but would probably generate a naked singularity at the front of the bubble.[6][7]

Difficulties

Significant problems with the metric of this form stem from the fact that all known warp drive spacetimes violate various energy conditions.[8] It is true that certain experimentally verified quantum phenomena, such as the Casimir effect, when described in the context of the quantum field theories, lead to stress–energy tensors that also violate the energy conditions, such as negative mass-energy, and thus one can hope that Alcubierre-type warp drives can be physically realized by clever engineering taking advantage of such quantum effects. However, if certain quantum inequalities conjectured by Ford and Roman hold,[9] then the energy requirements for some warp drives may be absurdly gigantic, e.g. the energy equivalent of -10^{64} kg might be required[10] to transport a small spaceship across the Milky Way galaxy. This is orders of magnitude greater than the estimated mass of the universe. Counter-arguments to these apparent problems have also been offered.[2]

Chris Van Den Broeck, in 1999, has tried to address the potential issues.[11] By contracting the 3+1 dimensional surface area of the 'bubble' being transported by the drive, while at the same time expanding the 3 dimensional volume contained inside, Van Den Broeck was able to reduce the total energy needed to transport small atoms to less than 3 solar masses. Later, by slightly modifying the Van Den Broeck metric, Krasnikov reduced the necessary total amount of negative energy to a few milligrams.[2][8]

Krasnikov proposed that, if tachyonic matter cannot be found or used, then a solution might be to arrange for masses along the path of the vessel to be set in motion in such a way that the required field was produced. But in this case, the Alcubierre Drive vessel is not able to go dashing around the galaxy at will. It is only able to travel routes which, like a railroad, have first been equipped with the necessary infrastructure. The pilot inside the bubble is causally disconnected with its walls and cannot carry out any action outside the bubble. Thus, because the pilot cannot place infrastructure ahead of the bubble while "in transit", the bubble cannot be used for the *first* trip to a distant star. In other words, to travel to Vega (which is 25 light-years from the Earth) one first has to arrange everything so that the bubble moving toward Vega with a superluminal velocity would appear and these arrangements will always take more than 25 years.[5]

Coule has argued that schemes such as the one proposed by Alcubierre are infeasible as matter placed *en route* of the intended path of a craft has to be placed at superluminal speed. Thus, according to Coule, an Alcubierre Drive is required in order to build an Alcubierre Drive. Since none have been proven to exist already then the drive is impossible to construct, even if the metric is physically meaningful. Coule argues that an analogous objection will apply to *any* proposed method of constructing an Alcubierre Drive.[7]

A paper by José Natário published in 2002 argued that it would be impossible for the ship to send signals to the front of the bubble, meaning that crew members could not control, steer or stop the ship.[12]

A more recent paper by Carlos Barceló, Stefano Finazzi, and Stefano Liberati makes use of quantum theory to argue that the Alcubierre Drive at FTL velocities is impossible; mostly due to extremely high temperatures caused by Hawking radiation destroying anything inside the bubble at superluminal velocities and leading to instability of the bubble itself. These problems do not arise if the bubble velocity is kept subluminal, but it is still necessary to provide exotic matter for the drive to work.[13]

More difficulties emerge in regards to the amount of exotic matter required for such a propulsion. According to Pfenning and Allen Everett of Tufts, a warp bubble traveling at 10 times light-speed must have a wall thickness of no more than 10^{-32} meters. This is close to the limiting Planck length, 1.6 x 10^{-35} metres. A bubble macroscopically large enough to enclose a ship 200 meters across would require a total amount of exotic matter equal to 10 billion times the mass of the observable universe. Straining the exotic matter to an extremely thin band of 10^{-32} meters is considered impractical. Similar constraints apply to Krasnikov's superluminal subway. A modification of Alcubierre's model was recently constructed by Chris van den Broeck of the Catholic University of Louvain in Belgium. It requires much less exotic matter but places the ship in a curved space-time "bottle" whose neck is about 10^{-32} meters. So-called cosmic strings, hypothesized in some cosmological theories, involve very large energy densities in long, narrow lines. But[*clarification needed*] all known physically reasonable cosmic-string models have positive (positive space-time warping effects) energy densities. These results seem to make it rather unlikely that one could construct Alcubierre warp drives using exotic matter generated by quantum effects.

Recent Discovery Revealed Suggests That Significantly Less Energy Than Proposed By Alcubierre's Theorum Is Required To Achieve Warp Travel

A group of physicists now say that adjustments can be made to the proposed warp drive that would enable a space craft to run on significantly less energy than what was originally theorized by Alcubierre, potentially bringing the idea back from the realm of science fiction into science.

On September 14, 2012, NASA scientists announced that they may have solved the

"Jupiter mass energy" problem with the Alcubierre drive theory – which theorized an energy mass equivalent to the planet Jupiter needed to power the drive. The new calculations are based on a modification of the shape of the disc surrounding the space craft which may result in a dramatic reduction of energy mass required to achieve warp travel. http://www.space.com/17628-warp-drive-possible-interstellar-space-flight.html

An Alcubierre warp drive would involve a football-shape spacecraft attached to a large ring encircling it. This ring, potentially made of exotic matter, would cause space-time to warp around the starship, creating a region of contracted space in front of it and expanded space behind. Meanwhile, the starship itself would stay inside a bubble of flat space-time that wasn't being warped at all. "Everything within space is restricted by the speed of light," explained Richard Obousy, president of Icarus Interstellar, a non-profit group of scientists and engineers devoted to pursuing interstellar spaceflight. "But the really cool thing is space-time, the fabric of space, is not limited by the speed of light." With this concept, the spacecraft would be able to achieve an effective speed of about 10 times the speed of light, all without breaking the cosmic speed limit. The only problem is, previous studies estimated the warp drive would require a minimum amount of energy about equal to the mass-energy of the planet Jupiter.

Harold "Sonny" White of NASA's Johnson Space Center said on September 14th, 2012, that he calculated what would happen if the shape of the ring encircling the spacecraft was adjusted into more of a rounded donut, as opposed to a flat ring. He found in that case, the warp drive could be powered by a mass about the size of a spacecraft like the Voyager 1 probe NASA launched in 1977. Furthermore, if the intensity of the space warps can be oscillated over time, the energy required is reduced even more, White found.

These results were presented at the 100 Year Starship Symposium, and announced that the United States space agency would pursue small-scale laboratory tests of the physics to confirm the theory, with the goal of creating a micro-version of a space-time warp at "tabletop" scales using the White-Juday Warp Field Interferometer at the center. http://www.space.com/17628-warp-drive-possible-interstellar-space-flight.html

"The findings I presented today change it from impractical to plausible and worth further investigation," says White. "The additional energy reduction realized by oscillating the bubble intensity is an interesting conjecture that we will enjoy looking at in the lab." http://www.space.com/17628-warp-drive-possible-interstellar-spaceflight.html

(Properly number citations above in citation section titled "NOTES" below.)

In science fiction

Faster-than-light travel is often used in science fiction to denote a wide variety of imaginary propulsion methods, though not necessarily based on the Alcubierre drive or any other physical theory.

The term "warp drive" is used for the method of FTL travel in Star Trek, chosen simply as a generic that sounded interesting during production.[*citation needed*]. Alcubierre stated in an email to William Shatner that his theory was directly inspired by the term used in the show,[14] and references it in his 1994 paper.[15]

Some science-fiction works, particularly of the 'hard' genre, have explicitly made use of the Alcubierre theory, such as Stephen Baxter's novel *Ark*.

The Alcubierre drive theory is proposed as a possible reason for events occurring in the graphic novel "Orbiter" by Warren Ellis and Colleen Doran.

The Ian Douglas "Star Carrier" series exclusively uses the Alcubierre drive as the main mode of interstellar travel.

Also, in M. John Harrison's novel *Light*, the character Ed Chianese, while trying to get a job with the Circus of Pathet Lao, claims that he "rode navigator on Alcubierre ships."

See also

- Exact solutions in general relativity (for more on the sense in which the Alcubierre spacetime is a solution).
- Spacecraft propulsion
- Faster-than-light
- Krasnikov Tube

Notes

1. ^ *a b c d* Alcubierre, Miguel (1994). "The warp drive: hyper-fast travel within general relativity". *Classical and Quantum Gravity* **11** (5): L73–L77. arXiv:gr-qc/0009013. Bibcode 1994CQGra..11L..73A. doi:10.1088/0264-9381/11/5/001.
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14. http://www.alan-shapiro.com/the-physics-of-warp-drive/
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External links

- The warp drive: hyper-fast travel within general relativity - Alcubierre's original paper *(PDF File)*
- Problems with Warp Drive Examined - *(PDF File)*

- Marcelo B. Ribeiro's Page on Warp Drive Theory
- A short video clip of the hypothetical effects of the warp drive.
- The (Im) Possibility of Warp Drive (Van Den Broeck)
- Reduced Energy Requirements for Warp Drive (Loup, Waite)
- Warp Drive Space-Time (González-Díaz)
- The Alcubierre Warp Drive: On the Matter of Matter (McMonigal, Lewis, O'Byrne) - *(PDF File)*
- "Ideas Based On What We'd Like To Achieve". NASA. It describes the concept in laymans terms