Record: 1

Title:	Will dark energy TEAR the universe apart? (cover story)
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Source:	Astronomy; Feb2009, Vol. 37 Issue 2, p34-39, 6p
Document Type:	Article
Subject Terms:	COSMOLOGY EXPANDING universe DARK energy (Astronomy) END of the universe ASTROPHYSICS
Abstract:	The article discusses dark energy and its potential role in a scenario in which matter in the universe expands to the point of ripping apart. Experiments in 1929 showed that the universe is expanding; in 1998, new experiments suggested the rate of expansion is accelerating, and this is attributed to dark energy. How the universe might end depends on the nature of dark energy, and weather expansion slows down, stays constant, or speeds up. If it speeds up, the universe could end in a "Big Rip." INSET: Cosmology and its crucial observations.
Lexile:	1150
Full Text Word Count:	3264
ISSN:	00916358
Accession Number:	35912815
Database:	Middle Search Plus

Section: The Big Rip

Will dark energy TEAR the universe apart?

Our cosmic fate depends on the biggest unknown in science.

Ten years ago cosmologists made a discovery that shook the world of science: Something is accelerating the universe's rate of expansion. They termed this something "dark energy," but its composition remains unknown. Whatever dark energy is, it dictates the universe's expansion rate and ultimate fate.

If the universe's expansion accelerates at an increasing rate, the energy density associated with dark energy would eventually strip apart gravitationally bound objects. I don't just mean that dark energy would rip galactic superclusters from each other. In this increasingly accelerated expansion, dark energy would rip the Local Group apart, rip Earth from the Sun, and ultimately rip even atoms apart. This violent scenario -- the Big Rip -- could be the universe's swan song.

The universe's stuff

A plethora of astronomical observations has led cosmologists to more accurately refine the percentage of matter density and energy density (energy per unit volume) in the universe. The most important of these observations include cosmic microwave background (CMB) experiments, quasar studies, gravitational lensing, galaxy structure surveys, and supernovae studies (see "Cosmology and its crucial observations," page 36).

The fact that the universe is expanding can be traced back to observations by Edwin Hubble and Milton Humason in 1929. In 1998, two separate groups of astrophysicists --

one led by Brian Schmidt of the Australian National Observatory and the other directed by Saul Perlmutter of Lawrence Berkeley National Laboratory -- discovered that the universe's expansion is accelerating. Both of the findings rely on observational tools called "standard candles."

A standard candle is a type of object that has a certain intrinsic brightness. Therefore, how bright the object appears depends on your distance from it. Think of automobile headlights. You can estimate how far away you are from a car depending on how bright the headlights appear.

Hubble used a type of variable star called a Cepheid as a standard candle to determine the distances to galaxies.

The period of a Cepheid variable star is related to its luminosity. By observing the period and the brightness of the Cepheid, Hubble could compare the observed brightness with the intrinsic luminosity to determine the distance to the Cepheid.

Knowing only the distance, though, isn't enough to conclude the universe is expanding. Hubble also looked at the spectra of those galaxies and saw that spectral lines were shifted toward the red end of the spectrum. This "redshift" means the object is moving away from the observer. Hubble compared the distances (obtained via Cepheid observations) with how fast the galaxies appear to be moving away and noticed a direct correlation: The farther away the galaxy, the faster the galaxy moves. The universe is expanding!

Schmidt and Perlmutter's teams used type Ia supernovae -- a different sort of standard candle -- for their observations. A type Ia supernova originates from a white dwarf star that is part of a binary star system. The white dwarf pulls material from its binary companion, and once the white dwarf reaches a critical mass -- 1.4 times that of the Sun -- it begins to collapse. The star doesn't collapse much before the remaining material ignites, and then the star explodes with a fantastically bright blast. Because all type Ia supernovae originate from white dwarfs of the same mass, they all have a similar luminosity.

Both groups observed the light curves from type Ia supernovae and found that the more distant supernovae (which are from an earlier time) were dimmer than expected if the universe was expanding at a constant rate. This means that the distances between those supernovae and the telescopes that observed them are greater than predicted. The universes expansion has accelerated over time!

So, what is the stuff -- dubbed "dark energy" -- that's accelerating the expansion rate? This question is one of the biggest facing science today.

Everything that we directly observe -- people, stars, interstellar medium -- composes only about 4.6 percent of our universe. What about the other 95.4 percent? Through supernova observations and CMB observations, astrophysicists have determined that roughly 23 percent of the universe is something called dark matter and about 72 percent is dark energy. Dark matter interacts via the gravitational force but not the electromagnetic force, meaning scientists know the matter exists, but there's no way to observe it directly. Dark energy is even more bizarre. Most of what astronomers know about dark energy is that it can be any type of uniform negative pressure energy and that it accelerates the universe's expansion.

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What is dark energy?

Even though cosmologists aren't sure what dark energy is, they have a few ideas. Scientists have three possible dark energy candidates: quintessence, vacuum energy, and phantom energy. Each would result in a different ending to our universe. Which scenario occurs depends both on the value of one parameter and whether that parameter changes in time. This parameter, called the equation of state, w, is the ratio between pressure and energy density (see "The parameter everything hinges on," page 37).

A positive value of the equation of state would cause deceleration in the universe as a result of the gravitational force. Each dark energy candidate has negative pressure and therefore a negative equation of state parameter. In fact, in order to generate acceleration, the total amount of "stuff" in the universe must have an equation of state value more negative than $-^{1}/_{3}$. The value also determines how fast the universe expands. And there's more: The equation of state value does not need to remain constant; it can vary in time.

Cosmologists split the dark energy candidates by their equation of state values. Quintessence has a value between $-^{1}/_{3}$ and -1. It is a dynamic field, meaning its density could change over time or from one place to another in the universe.

Vacuum energy gets its name from its role as the energy of "empty" space. Space is filled with a smooth energy density of virtual particles (particle-antiparticle pairs) that pop in and out of existence. Vacuum energy can be represented by the cosmological constant term in Albert Einstein's general theory of relativity because both have an equation of state value of -1 and therefore have constant density as the universe expands. Einstein initially coined the term "cosmological constant" to fit into his static universe model. After Hubble discovered the universe is expanding, Einstein retracted the idea of the cosmological constant, calling it his greatest "blunder."

While the cosmological constant looks promising as a result of its energy density -- an equation of state of -1 closely fits CMB observations -- the problem arises when physicists calculate how much vacuum energy is expected in the universe. The standard model of particle physics predicts 10120 times more vacuum energy than what scientists observe.

An equation of state parameter more negative than -1 corresponds to phantom energy -- the third dark energy candidate. In this scenario, the universe would become progressively more dark-energy-dominated, and acceleration therefore would increase dramatically. So what could this phantom energy be? While vacuum energy comprises virtual particles, "phantom energy might be a perverse type of particle that relaxes by vibrating faster and faster," says Robert Caldwell of Dartmouth College, lead author of a 2003 Physical Review Letters article about phantom energy and its implications for the universe's future.

In the cosmological constant scenario, the energy density stays constant; in the phantom energy scenario, the energy density increases. Yet one would expect the energy density of dark energy to decrease as the universe expands in the same way a few drops of colored dye dilutes in a tub of water. How do modern cosmological theories argue the energy density stays constant or even increases? Marc Kamionkowski of the California Institute of Technology explains, "Whether the energy density dilutes or not depends on the equation of state of the dark energy."

To further understand this concept, compare a box filled with hot gas to a region of the expanding universe that you observe. (This area is called a "co-moving" region because

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you as an observer are moving with the region you're observing.) In the box, Kamionkowski explains, "the high pressure associated with the heat may push the walls of the box outward. The heat energy in the box then decreases, but energy is still conserved. The energy lost from the box transfers some energy to the outward motion of the walls. Likewise, in an expanding universe, the change in the energy in a co-moving region of the universe goes toward pushing the adjacent regions of the universe outward."

Recall that the dark energy equation of state is negative; therefore the pressure is negative, and, says Kamionkowski, "so the energy per co-moving region in the universe actually increases. With a cosmological constant, the energy increase is just large enough to keep the energy density constant, but the energy per co-moving volume is still increasing. Phantom energy is not too much different, but the energy increase is just a little bigger."

Like all dark energy candidates, phantom energy has not been directly observed, and many questions remain unanswered. But also like the other dark energy possibilities, cosmologists can extrapolate to the universes future and infer how each dark energy candidate dictates the universe's end.

Our ultimate fate

The poet Robert Frost wrote, "Some say the world will end in fire / Some say in ice." But the universe might hold in store a more violent end. Cosmologists have theorized many ending scenarios to our universe, but its ultimate fate will depend on the behavior of dark energy.

If the dark energy density were to disappear, matter and radiation ultimately would dominate the energy density of the universe. In this scenario -- the Big Crunch -- the attractive gravitational force would take over, and the universe's contents would collapse into a singularity -- likely a black hole. Given what scientists know about dark energy (mainly that it is accelerating the expansion), this Big Crunch scenario is not the most likely ending. However, one can't rule it out.

What if the dark energy density stays constant as the universe expands, as occurs in the cosmological constant scenario? In this situation -- the Big Chill -- the universe's expansion would continue to accelerate, but the acceleration would not increase. Stars will burn out, galaxies will pass beyond the Hubble distance, and space will become empty and cold. The CMB radiation (the radiation that permeates space) will cool to just a fraction of a degree above absolute zero. In the Big Chill, the universe doesn't actually end; it expands forever.

If dark energy is phantom energy, however, we can count on a far more violent end to our universe -- the Big Rip.

The Big Rip

Recall that if the equation of state is less than -1, and dark energy is phantom energy, the universe would become increasingly dark-energy-dominated and the acceleration would increase. When playing out this scenario, the scale factor -- the relative expansion of the universe -- blows up to infinity. As the scale factor grows larger than the Hubble distance, galaxies disappear beyond the horizon of the observable universe. Similar to the Big Chill, any observers left on Earth would see fewer galaxies. The big difference, however, between the Big Chill and the Big Rip is what occurs next.

Phantom energy will strip apart gravitationally bound objects. Everything in the universe that is held by the gravitational force will dissociate. The horizon radius shrinks to a point,

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and all matter will rip apart. First, the Local Group of galaxies will be ripped apart, followed by the Milky Way Galaxy. As phantom dark energy continues to increase, it will rip our planet from the Sun roughly a year before the end of the universe. About 1 hour before the end, phantom energy will tear Earth apart. But it won't stop there.

After all gravitationally bound objects are ripped apart, and just fractions of a second before the end of the universe, phantom energy will rip apart all objects held together via electromagnetic and strong forces. These objects include molecules, atoms, and even subatomic particles. Then the universe will end in a singularity, but a different sort of singularity than the Big Bang and the Big Crunch. In this scenario, instead of all matter and radiation being squashed together, all the universe's components would be ripped apart to infinity.

And that is the Big Rip. It sounds great, doesn't it?

Fortunately, there's no need to worry quite yet. The Big Rip "would not be before [about] 55 billion years in the future, if at all," Caldwell says. Some calculations say it would occur almost 90 billion years from now.

Kamionkowski, co-author of the 2003 article about phantom energy and the Big Rip, explains: "If w is far less than -1, then the Big Rip occurs relatively soon. If it is extremely close to -1, but still less than -1, then the Big Rip occurs later." The key is to narrow the value of w, the equation of state. "Over the past 5 years, observations have constrained w to be closer to -1," he says.

Remember that an equation of state value of -1 corresponds to the cosmological constant. That's how close these two scenarios are. A value of -1 implies a Big Chill, while a value less than -1 leads to a Big Rip. "It could be that the true w takes the value of -1.05, which is also consistent with current data, and yet it will lead to the Big Rip," explains Dragan Huterer of the University of Michigan.

The possibility of the Big Rip, and when it would occur, teeters on the value of one parameter. Now cosmologists just need to determine that value and whether it holds constant.

Explaining astronomy's standard candles

• **As photons beam** outward from a light source, they spread out over an ever-greater area. The total light the source produces (its intrinsic brightness) remains constant; but the amount of light an observer sees (the source's apparent brightness) decreases with distance at a predictable rate. As a result, the difference between intrinsic and apparent brightness reveals the observer's distance from the light source.

At one unit of distance, the light covers a one by one area.

At two units of distance, the light spreads out over four times the area, so it is ¼ as bright at any given point.

At three units of distance, the light is $^1/_9$ as bright.

• **Astronomers** compare a supernova's intrinsic brightness to its brightness as measured from Earth. The difference reveals the distance to the supernova and, therefore, its host

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galaxy. Scientists have found that more distant supernovae (from an earlier time) are fainter then predicted. This implies that those supernovae are farther away than expected.

In 2006, a type Ia supernova, called 2006X, blazed in the spiral galaxy M100 (left).

The parameter everything hinges on

The equation of state, w, does not characterize only a dark energy candidate. The following table shows various values for w and what that value represents.

Equation of state value (w)	What that value represents
w = 1/3	Electromagnetic radiation
w = 0	Non-relativistic matter
w = 1	Relativistic matter
w = -1	Cosmological constant, A; vacuum energy
-1/3 > w > -1	Quintessence; the value of w can change with time
w < -1	Phantom energy

The Big Rip Scenario

The future of our universe depends on what dark energy is. If dark energy is phantom energy, the universe's accelerated expansion will increase dramatically and lead the universe to a Big Rip. This timeline shows both the universe's past (from observations and computations) and future (if we're heading for a Big Rip). In this case, the equation of state is -1.1, which places the Big Rip at roughly 86 billion years in the future.

Time after the Big Bang

10^{-43} second: Planck era ends

10^{-35} second: Inflation

10^{-32} second: Quark and antiquark pairs formed

3 minutes: Light elements (hydrogen, deuterium, helium, lithium, and beryllium) formed

10,000: years Atoms formed

380,000 years: Photons fly free, cosmic microwave background (CMB)

1 billion years: First galaxies formed

13.7 billion years: Today

Time before the Big Rip

t_{rip} -3 billion years: Galaxy clusters erased

t_{rip} -200 million years: Milkomeda destroyed

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t_{rip} -1 year: Solar system unbound

t_{rip} -1 hour: Earth explodes

t_{rip} -10t^{-19} second: Atoms ionize

t_{rip} - <10t^{-22} second: Nuclei and nucleons dissociate

t_{rip} = ~100 billion years: The Big Rip

GLOSSARY OF TERMS

Observable universe

The region of the universe that astronomers can observe. It's governed by the finite speed of light and the universe's age: 13.7 billion years. As far as we know, beyond this limit, the universe could be infinite. Many use the term "universe" to mean the observable universe.

Scale Factor

A function of time that represents the relative size of the expanding universe; the current value is 1.

Hubble length

The radius of the observable universe, which is the region of the universe that astronomers can observe.

Singularity

A point at which space and time are extremely distorted; where the curvature of the universe goes to zero or infinity.

DIAGRAM: Explaining astronomy's standard candles

PHOTO (COLOR): In the future, all galaxies could be ripped apart before the universe's violent end -- the Big Rip. Whether the Big Rip occurs depends on what dark energy is. In the Big Rip scenario, after dark energy rips galaxies apart, it would unbind the solar system and tear Earth apart. Eventually, after all gravitationaliy bound bodies are ripped apart, atoms and particles would follow.

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By Liz Kruesi

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Cosmology and its crucial observations

Learning about the composition of our universe has involved multiple astronomical surveys. Below are a collection of the types of observations that have led to astronomers' current understanding of the universe.

• **Gravitational lensing** showed that galaxy clusters must have additional mass that isn't luminous. A massive object -- in this case, a cluster of galaxies -- can warp space-time. The light from a distant object follows this bent space-time, which allows the observer to see what sits behind the galaxy cluster. The luminous mass in a galaxy cluster is not enough alone to warp space.

• **Galaxy structure surveys** showed that luminous matter (galaxy clusters) clumps in the same way as expected by dark matter simulations. Luminous matter follows the lead of dark matter because of the gravitational force.

• **Type Ia supernovae** observations indicated the universe's expansion is accelerating. Higher redshift type Ia supernovae (those that are further back in time and therefore farther away) are dimmer than expected. Astronomers concluded the supernovae must be even more distant than expected, which means the universe's expansion is increasing.

• **Cosmic microwave background** (CMB) observations first showed in the 1960s that microwave radiation emanates from all directions in space. This observation was evidence for the Big Bang as the universe's beginning. A number of CMB experiments have narrowed down CMB characteristics, but the most recent experiment, the Wilkinson Microwave Anisotropy Probe (WMAP), has been crucial in determining many of the universe's parameters. WMAP, which launched June 2001, has since measured the temperature of the universe (2.725 kelvin), how old it is (13.7 billion years), the percentage of stuff in the universe (4.6 percent normal matter, 23 percent dark matter, 72 percent dark energy; all within 1 percent), and the geometry of the universe (mostly flat).

By compiling data from observations of galaxy clusters, the cosmic microwave background, and distant supernovae, cosmologists have gained a better understanding of the universe's components, history, and future.

DIAGRAM: Cosmology and its crucial observations

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