{{noteTA

|1=zh-hans:引力; zh-hant:重力;

|2=zh-hans:万有引力; zh-hant:萬有引力;

}}

[[File:PIA17993-DetectorsForInfantUniverseStudies-20140317.jpg|thumb|200px|right|[[BICEP2]][[射電望遠鏡]]有可能發現了[[大爆炸]]後早期宇宙所產生的[[重力波]]的證據。<ref name="BICEP2-2014" /><ref name="NASA-20140317" /><ref name="NYT-20140317" /><ref name="NYT-20140324" />]]

在[[物理宇宙學]]中，'''宇宙暴脹'''，簡稱'''暴脹'''，是早期[[宇宙]]的一種快速[[空間的度規膨脹|空間膨脹]]過程。[[暴脹時期]]在[[大爆炸]]後10<sup>−36</sup>秒開始，持續到大爆炸後10<sup>−33</sup>至10<sup>−32</sup>秒之間，膨脹速度遠超過[[光速]]。暴脹之後，宇宙繼續膨脹，但速度則低得多。

「暴脹」一詞可以指有關暴脹的假說、暴脹理論或者暴脹時期。這一假說以及「暴脹」一詞，最早於1980年由美國物理學家[[阿蘭·古斯]]提出。<ref>Chapter 17 of Peebles (1993).</ref>

2014年3月17日，[[BICEP2]]科學家團隊宣佈在[[B模]][[功率譜]]中可能探測到暴脹所產生的[[重力波 (相對論)|重力波]]。這為暴脹理論提供了強烈的證據，對於標準宇宙學來說是一項重要的發現 。<ref name="BICEP2-2014">{{cite web |authors=Staff |title=BICEP2 2014 Results Release |url=http://bicepkeck.org |date=17 March 2014 |work=[[National Science Foundation]] |accessdate=18 March 2014 }}</ref><ref name="NASA-20140317">{{cite web |last=Clavin |first=Whitney |title=NASA Technology Views Birth of the Universe |url=http://www.jpl.nasa.gov/news/news.php?release=2014-082 |date=17 March 2014 |work=[[NASA]] |accessdate=17 March 2014 }}</ref><ref name="NYT-20140317">{{cite news |last=Overbye |first=Dennis |authorlink=Dennis Overbye |title=Space Ripples Reveal Big Bang’s Smoking Gun |url=http://www.nytimes.com/2014/03/18/science/space/detection-of-waves-in-space-buttresses-landmark-theory-of-big-bang.html |date=17 March 2014 |work=[[The New York Times]] |accessdate=17 March 2014 }}</ref><ref name="NYT-20140324">{{cite news |last=Overbye |first=Dennis |authorlink=Dennis Overbye |title=Ripples From the Big Bang |url=http://www.nytimes.com/2014/03/25/science/space/ripples-from-the-big-bang.html |date=24 March 2014 |work=[[New York Times]] |accessdate=24 March 2014 }}</ref><ref>{{cite journal|title=BICEP2 I: Detection of ''B''-mode Polarization at Degree Angular Scales|first1=P. A. R.|last1=Ade|first2=R. W.|last2=Aikin|first3=D.|last3=Barkats|first4=S. J.|last4=Benton|first5=C. A.|last5=Bischoff|first6=J. J.|last6=Bock|first7=J. A.|last7=Brevik|first8=I.|last8=Buder|first9=E.|last9=Bullock|first10=C. D.|last10=Dowell|first11=L.|last11=Duband|first12=J. P.|last12=Filippini|first13=S.|last13=Fliescher|first14=S. R.|last14=Golwala|first15=M.|last15=Halpern|first16=M.|last16=Hasselfield|first17=S. R.|last17=Hildebrandt|first18=G. C.|last18=Hilton|first19=V. V.|last19=Hristov|first20=K. D.|last20=Irwin|first21=K. S.|last21=Karkare|first22=J. P.|last22=Kaufman|first23=B. G.|last23=Keating|first24=S. A.|last24=Kernasovskiy|first25=J. M.|last25=Kovac|first26=C. L.|last26=Kuo|first27=E. M.|last27=Leitch|first28=M.|last28=Lueker|first29=P.|last29=Mason|first30=C. B.|last30=Netterfield|first31=H. T.|last31=Nguyen|first32=R.|last32=O'Brient|first33=R. W. IV|last33=Ogburn|first34=A.|last34=Orlando|first35=C.|last35=Pryke|first36=C. D.|last36=Reintsema|first37=S.|last37=Richter|first38=R.|last38=Schwartz|first39=C. D.|last39=Sheehy|first40=Z. K.|last40=Staniszewski|first41=R. W.|last41=Sudiwala|first42=G. P.|last42=Teply|first43=J. E.|last43=Tolan|first44=A. D.|last44=Turner|first45=A. G.|last45=Vieregg|first46=C. L.|last46=Wong|first47=K. W.|last47=Yoon|date=17 March 2014|arxiv=submit/0934323|url=http://bicepkeck.org/b2\_respap\_arxiv\_v1.pdf|format=PDF}}</ref>然而，除此之外還有非標準宇宙學理論，包括前大爆炸理論和[[旋量]]時空理論等。<ref name="Gonzalez-MestresSST1">{{cite web |authors=Luis Gonzalez-Mestres |title=Space, Time and Superluminal Particles |url=http://arxiv.org/abs/physics/9702026 |date=24 February 1997}}</ref><ref group="注">一般來說，暴脹在前大爆炸理論中並不是必須的。路易斯·貢薩雷斯-梅斯特雷斯（Luis Gonzalez-Mestres）在1996至1997年所提出的旋量時空理論中，每一個隨動觀測者都會產生一個特殊的空間方向，而[[宇宙微波背景]]中也會自然存在B模。[[普朗克衛星]]數據可能證實了這一特殊空間方向的存在。</ref><ref name="Gonzalez-MestresSST2">{{cite web |authors=Luis Gonzalez-Mestres |title=BICEP2, CMB B-modes And Spinorial Space-time |url=http://www.science20.com/relativity\_and\_beyond\_it/bicep2\_cmb\_bmodes\_and\_spinorial\_spacetime-132616 |date=26 March 2014}}</ref><ref name="Gonzalez-MestresBICEP2-I">{{cite web |authors=Luis Gonzalez-Mestres |title=CMB B-modes, spinorial space-time and Pre-Big Bang (I) |url=http://www.ma.utexas.edu/mp\_arc/c/14/14-16.pdf |date=28 March 2014}} (University of Texas Mathematical Physics Archive, paper 14-16).</ref><ref>{{cite web |authors=Ron Cowen |title=Cosmologists at odds over mysterious anomalies in data from early Universe |url=http://www.nature.com/news/cosmologists-at-odds-over-mysterious-anomalies-in-data-from-early-universe-1.14368 |date=13 December 2013}} (Nature News)</ref>

暴脹的直接結果，是宇宙在各個方向都顯得相同，即[[各向同性]]，以及平均分佈的[[宇宙微波背景]]輻射。微觀時期的[[量子漲落]]經暴脹放大至宇宙級大小，這解釋了宇宙宏觀結構的形成。<ref>Tyson, Neil deGrasse and Donald Goldsmith (2004), ''Origins: Fourteen Billion Years of Cosmic Evolution'', W. W. Norton & Co., pp. 84–5.</ref>

雖然暴脹的詳細[[粒子物理學]]原理還沒有被發現，但是基本理論所作出了多項預測已經被觀測所證實。<ref>{{cite journal|author=Tsujikawa, Shinji|title=Introductory review of cosmic inflation|date=28 Apr 2003|journal=ArXiv.org}}</ref>導致暴脹的假想[[基本粒子|粒子]]或[[場 (物理)|場]]稱為[[暴脹子]]。<ref>{{cite book|author=Guth, Alan H.|authorlink=Alan Guth|title=The Inflationary Universe: The Quest for a New Theory of Cosmic Origins|year=1997|publisher=Basic Books|pages=233–234|url=http://books.google.com/books?id=7toILlSQtI0C&pg=PA233|isbn=0201328402}}</ref>

==概述==

{{Main|Metric expansion of space}}

{{Technical|date=November 2010|section}}

An expanding universe generally has a [[Cosmological horizon#Cosmological horizon|cosmological horizon]], which, by analogy with the more familiar [[horizon]] caused by the curvature of the Earth's surface, marks the boundary of the part of the universe that an observer can see. Light (or other radiation) emitted by objects beyond the cosmological horizon never reaches the observer, because the space in between the observer and the object is expanding too rapidly.

The [[observable universe]] is one ''causal patch'' of a much larger unobservable universe; there are parts of the universe that cannot communicate with us yet. These parts of the universe are outside our current cosmological horizon. In the standard hot big bang model, without inflation, the cosmological horizon moves out, bringing new regions into view. Yet as a local observer sees these regions for the first time, they look no different from any other region of space the local observer has already seen: they have a background radiation that is at nearly exactly the same temperature as the background radiation of other regions, and their space-time curvature is evolving lock-step with ours. This presents a mystery: how did these new regions know what temperature and curvature they were supposed to have? They couldn't have learned it by getting signals, because they were not in communication with our past [[light cone]] before.<ref name="tiny">[http://www.npr.org/templates/story/story.php?storyId=102715275 Using Tiny Particles To Answer Giant Questions]. Science Friday, 3 April 2009.</ref><ref>See also [[Faster than light#Universal expansion]].</ref>

[[File:History of the Universe.svg|thumb|left|350px|History of the [[Universe]] - [[gravitational waves]] are hypothesized to arise from cosmic inflation, a [[Faster-than-light#Universal expansion|faster-than-light]] expansion just after the [[Big Bang]] (17 March 2014).<ref name="BICEP2-2014" /><ref name="NASA-20140317" /><ref name="NYT-20140317" />]]

Inflation answers this question by postulating that all the regions come from an earlier era with a big vacuum energy, or cosmological constant. A space with a cosmological constant is qualitatively different: instead of moving outward, the cosmological horizon stays put. For any one observer, the distance to the [[Observable universe#Cosmological horizon|cosmological horizon]] is constant. With exponentially expanding space, two nearby observers are separated very quickly; so much so, that the distance between them quickly exceeds the limits of communications. The spatial slices are expanding very fast to cover huge volumes. Things are constantly moving beyond the cosmological horizon, which is a fixed distance away, and everything becomes homogeneous very quickly.

As the inflationary field slowly relaxes to the vacuum, the cosmological constant goes to zero, and space begins to expand normally. The new regions that come into view during the normal expansion phase are exactly the same regions that were pushed out of the horizon during inflation, and so they are necessarily at nearly the same temperature and curvature, because they come from the same little patch of space.

The theory of inflation thus explains why the temperatures and curvatures of different regions are so nearly equal. It also predicts that the total curvature of a space-slice at constant global time is zero. This prediction means that the total ordinary matter, [[dark matter]], and residual [[vacuum energy]] in the universe have to add up to the critical density, and the evidence strongly supports this. More strikingly, inflation allows physicists to calculate the minute differences in temperature of different regions from quantum fluctuations during the inflationary era, and many of these quantitative predictions have been confirmed.<ref name="wmap"/><ref>[http://www.space.com/14699-universe-inflation-cosmic-expansion-theory.html Our Baby Universe Likely Expanded Rapidly, Study Suggests]</ref>

===Space expands===

To say that space expands exponentially means that two [[Inertial frame of reference|inertial observer]]s are moving farther apart with accelerating velocity. In stationary coordinates for one observer, a patch of an inflating universe has the following [[polar coordinates|polar]] [[metric tensor|metric]]:<ref>Melia, Fulvio (2007), ''The Cosmic Horizon'', MNRAS, '''382''', 1917–1921.</ref><ref>Melia, Fulvio et al. (2009), ''The Cosmological Spacetime'', IJMP-D, '''18''', 1889–1901.</ref>

:<math>

ds^2 = - (1- \Lambda r^2) \, dt^2 + {1\over 1-\Lambda r^2} \, dr^2 + r^2 \, d\Omega^2.

</math>

This is just like an inside-out [[Schwarzschild metric|black hole metric]]—it has a zero in the <math>dt</math> component on a fixed radius sphere called the [[Observable universe#Particle horizon|cosmological horizon]]. Objects are drawn away from the observer at <math>r=0</math> towards the cosmological horizon, which they cross in a finite proper time. This means that any inhomogeneities are smoothed out, just as any bumps or matter on the surface of a black hole horizon are swallowed and disappear.

Since the [[space&ndash;time]] metric has no explicit time dependence, once an observer has crossed the cosmological horizon, observers closer in take its place. This process of falling outward and replacement points closer in are always steadily replacing points further out—an exponential expansion of space&ndash;time.

This steady-state exponentially expanding spacetime is called a [[de Sitter space]], and to sustain it there must be a [[cosmological constant]], a [[dark energy|vacuum energy]] proportional to <math>\Lambda</math> everywhere. In this case, the [[Equation of state (cosmology)|equation of state]] is <math>\! p=-\rho</math>. The physical conditions from one moment to the next are stable: the rate of expansion, called the [[Hubble parameter]], is nearly constant, and the scale factor of the universe is proportional to <math>e^{Ht}</math>. Inflation is often called a period of ''accelerated expansion'' because the distance between two fixed observers is increasing exponentially (i.e. at an accelerating rate as they move apart), while <math>\Lambda</math> can stay approximately constant (see [[deceleration parameter]]).

===Few inhomogeneities remain===

Cosmological inflation has the important effect of smoothing out [[homogeneity (physics)|inhomogeneities]], [[anisotropy|anisotropies]] and the [[shape of the universe|curvature of space]]. This pushes the universe into a very simple state, in which it is completely dominated by the inflaton field, the source of the cosmological constant, and the only significant inhomogeneities are the tiny quantum fluctuations in the inflaton. Inflation also dilutes exotic heavy particles, such as the [[magnetic monopole]]s predicted by many extensions to the [[Standard Model]] of [[particle physics]]. If the universe was only hot enough to form such particles ''before'' a period of inflation, they would not be observed in nature, as they would be so rare that it is quite likely that there are none in the [[observable universe]]. Together, these effects are called the inflationary "no-hair theorem"<ref>Kolb and Turner (1988).</ref> by analogy with the [[no hair theorem]] for [[black hole]]s.

The "no-hair" theorem works essentially because the cosmological horizon is no different from a black-hole horizon, except for philosophical disagreements about what is on the other side. The interpretation of the no-hair theorem is that the universe (observable and unobservable) expands by an enormous factor during inflation. In an expanding universe, [[energy density|energy densities]] generally fall, or get diluted, as the volume of the universe increases. For example, the density of ordinary "cold" matter (dust) goes down as the inverse of the volume: when linear dimensions double, the energy density goes down by a factor of eight; the radiation energy density goes down even more rapidly as the universe expands since the wavelength of each photon is stretched ([[redshift]]ed), in addition to the photons being dispersed by the expansion. When linear dimensions are doubled, the energy density in radiation falls by a factor of sixteen.

During inflation, the energy density in the inflaton field is roughly constant. However, the energy density in inhomogeneities, curvature, anisotropies and exotic particles is falling, and through sufficient inflation these become negligible. This leaves an empty, flat, and symmetric universe, which is filled with radiation when inflation ends.

===Key requirement===

A key requirement is that inflation must continue long enough to produce the present observable universe from a single, small inflationary [[Hubble volume]]. This is necessary to ensure that the universe appears flat, homogeneous and isotropic at the largest observable scales. This requirement is generally thought to be satisfied if the universe expanded by a factor of at least 10<sup>26</sup> during inflation.<ref>This is usually quoted as 60 ''e''-folds of expansion, where ''e''<sup>60</sup> ≈ 10<sup>26</sup>. It is equal to the amount of expansion since reheating, which is roughly ''E''<sub>inflation</sub>/''T''<sub>0</sub>, where ''T''<sub>0</sub> = 2.7 [[Kelvin|K]] is the temperature of the cosmic microwave background today. See, ''e.g.'' Kolb and Turner (1998) or Liddle and Lyth (2000).</ref>

===Reheating===

Inflation is a period of [[supercooled]] expansion, when the temperature drops by a factor of 100,000 or so. (The exact drop is model dependent, but in the first models it was typically from 10<sup>27</sup>K down to 10<sup>22</sup>K.<ref>Guth, ''Phase transitions in the very early universe'', in ''The Very Early Universe'', ISBN 0-521-31677-4 eds Hawking, Gibbon & Siklos</ref>) This relatively low temperature is maintained during the inflationary phase. When inflation ends the temperature returns to the pre-inflationary temperature; this is called ''reheating'' or thermalization because the large potential energy of the inflaton field decays into particles and fills the universe with [[Standard Model]] particles, including [[electromagnetic radiation]], starting the [[radiation-dominated era|radiation dominated phase]] of the Universe. Because the nature of the inflation is not known, this process is still poorly understood, although it is believed to take place through a [[parametric oscillator|parametric resonance]].<ref>See Kolb and Turner (1988) or Mukhanov (2005).</ref><ref>{{Cite journal|title=Reheating after inflation | doi = 10.1088/0264-9381/3/5/011|first=Lev|last=Kofman|journal=Physical Review Letters|volume=73|issue=5|year=1994|pages=3195&ndash;3198|arxiv=hep-th/9405187|last2=Linde|first2=Andrei|last3=Starobinsky|first3=Alexei|bibcode = 1986CQGra...3..811K }}</ref>

==Motivations==

Inflation resolves [[Big Bang#Problems|several problems]] in the [[Big Bang]] cosmology that were discovered in the 1970s.<ref>Much of the historical context is explained in chapters 15&ndash;17 of Peebles (1993).</ref>

Inflation was first discovered by Guth while investigating the problem of why no [[magnetic monopoles]] are seen today; he found that a positive-energy [[false vacuum]] would, according to [[general relativity]], generate an exponential expansion of space. It was very quickly realised that such an expansion would resolve many other long-standing problems. These problems arise from the observation that to look like it does ''today'', the universe would have to have started from very [[fine tuned universe|finely tuned]], or "special" initial conditions at the Big Bang. Inflation attempts to resolve these problems by providing a dynamical mechanism that drives the universe to this special state, thus making a universe like ours much more likely in the context of the Big Bang theory.

===Horizon problem===

{{Main|Horizon problem}}

The [[horizon problem]] is the problem of determining why the universe appears statistically homogeneous and isotropic in accordance with the [[cosmological principle]].<ref>{{Cite journal|title=The isotropy of the universe | doi = 10.1088/0264-9381/15/2/008|first=Charles W.|last=Misner|year=1968|journal=Astrophysical Journal|volume=151|issue=2|pages=431|last2=Coley|first2=A A|last3=Ellis|first3=G F R|last4=Hancock|first4=M|bibcode = 1998CQGra..15..331W }}</ref><ref name="mtw">{{Cite book| last = Misner | first = Charles | coauthors = Thorne, Kip S. and Wheeler, John Archibald | title = Gravitation | location = San Francisco | publisher = W. H. Freeman | year = 1973 | isbn = 0-7167-0344-0|pages=489&ndash;490, 525&ndash;526}}</ref><ref name="weinberg">{{Cite book| first = Steven | last = Weinberg | title = Gravitation and Cosmology | publisher = John Wiley | year = 1971 | isbn = 0-471-92567-5|pages=740, 815}}</ref> For example, molecules in a canister of gas are distributed homogeneously and isotropically because they are in thermal equilibrium: gas throughout the canister has had enough time to interact to dissipate inhomogeneities and anisotropies. The situation is quite different in the big bang model without inflation, because gravitational expansion does not give the early universe enough time to equilibrate. In a big bang with only the [[matter]] and [[radiation]] known in the [[Standard Model]], two widely separated regions of the observable universe cannot have equilibrated because they move apart from each other faster than the [[speed of light]]&mdash;thus have never come into [[causal contact]]: in the history of the universe, back to the earliest times, it has not been possible to send a light signal between the two regions. Because they have no interaction, it is difficult to explain why they have the same temperature (are thermally equilibrated). This is because the [[Hubble radius]] in a radiation or matter-dominated universe expands much more quickly than physical lengths and so points that are out of communication are coming into communication. Historically, two proposed solutions were the ''Phoenix universe'' of [[Georges Lemaître]]<ref>{{Cite journal|last=Lemaître|first=Georges|title=The expanding universe|journal=Annales de la Société Scientifique de Bruxelles|volume=47A|pages=49|year=1933}}, English in ''Gen. Rel. Grav.'' '''29''':641–680, 1997.</ref> and the related [[oscillatory universe]] of [[Richard Chase Tolman]],<ref>{{Cite book| author=R. C. Tolman | title= Relativity, Thermodynamics, and Cosmology | location=Oxford | publisher=Clarendon Press | year=1934| isbn=0-486-65383-8| lccn=340-32023}} Reissued (1987) New York: Dover ISBN 0-486-65383-8.</ref> and the [[Mixmaster universe]] of [[Charles Misner]].<ref name="mtw" /><ref>{{Cite journal|title=Mixmaster universe | doi = 10.1088/1751-8113/41/15/155201|first=Charles W.|last=Misner|year=1969|journal=Physical Review Letters|volume=22|issue=15|pages=1071&ndash;74|last2=Leach|first2=P G L|bibcode = 2008JPhA...41o5201A }}</ref> Lemaître and Tolman proposed that a universe undergoing a number of cycles of contraction and expansion could come into thermal equilibrium. Their models failed, however, because of the buildup of [[entropy]] over several cycles. Misner made the (ultimately incorrect) conjecture that the Mixmaster mechanism, which made the universe ''more'' chaotic, could lead to statistical homogeneity and isotropy.

===Flatness problem===

{{Main|Flatness problem}}

Another problem is the [[flatness problem]] (which is sometimes called one of the [[Dicke]] coincidences, with the other being the [[cosmological constant problem]]).<ref>{{Cite book|last=Dicke |first=Robert H.|title=Gravitation and the Universe |location = Philadelphia | publisher=American Philosopical Society | year = 1970}}</ref><ref>{{Cite conference|title=The big bang cosmology &ndash; enigmas and nostrums|first=Robert H.|last=Dicke|coauthors=P. J. E. Peebles | year = 1979| booktitle = General Relativity: an Einstein Centenary Survey|editor=ed. S. W. Hawking and W. Israel | publisher = Cambridge University Press}}</ref> It had been known in the 1960s{{Citation needed|date=February 2007}} that the density of matter in the universe was comparable to the [[Critical density (cosmology)|critical density]] necessary for a flat universe (that is, a universe whose large scale [[geometry]] is the usual [[Euclidean geometry]], rather than a [[non-Euclidean geometry|non-Euclidean]] [[hyperbolic geometry|hyperbolic]] or [[spherical geometry]]).

Therefore, regardless of the [[shape of the universe]] the contribution of spatial curvature to the expansion of the universe could not be much greater than the contribution of matter. But as the universe expands, the curvature [[redshift]]s away more slowly than matter and radiation. Extrapolated into the past, this presents a [[fine-tuning]] problem because the contribution of curvature to the universe must be exponentially small (sixteen orders of magnitude less than the density of radiation at [[big bang nucleosynthesis]], for example). This problem is exacerbated by recent observations of the cosmic microwave background that have demonstrated that the universe is flat to the accuracy of a few percent.<ref>[http://map.gsfc.nasa.gov/universe/uni\_matter.html What is the Universe Made Of?]</ref>

===Magnetic-monopole problem===

The [[Big Bang#Magnetic monopoles|magnetic monopole problem]] (sometimes called the exotic-relics problem) says that if the early universe were very hot, a large number of very heavy{{why|date=November 2012}}, stable [[magnetic monopole]]s would be produced. This is a problem with [[Grand Unified Theory|Grand Unified Theories]], which proposes that at high temperatures (such as in the early universe) the [[electromagnetic force]], [[strong nuclear force|strong]], and [[weak nuclear force|weak]] [[nuclear force]]s are not actually fundamental forces but arise due to [[spontaneous symmetry breaking]] from a single [[gauge theory]].<ref>Since [[supersymmetry|supersymmetric]] Grand Unified Theory is built into [[string theory]], it is still a triumph for inflation that it is able to deal with these magnetic relics. See, ''e.g.'' Kolb and Turner (1988) and {{Cite conference|title=Grand Unified Theories|first=Stuart|last=Raby|arxiv=hep-ph/0608183|booktitle=Galapagos World Summit on Physics Beyond the Standard Model|editor=ed. Bruce Hoeneisen|year=2006}}</ref> These theories predict a number of heavy, stable particles that have not yet been observed in nature. The most notorious is the magnetic monopole, a kind of stable, heavy "knot" in the magnetic field.<ref>{{Cite journal|last='t Hooft|first=Gerard|title=Magnetic monopoles in Unified Gauge Theories|journal=Nuclear Physics B|volume=79|pages=276&ndash;84|year=1974|bibcode=1974NuPhB..79..276T|doi=10.1016/0550-3213(74)90486-6|issue=2}}</ref><ref>{{Cite journal|first=Alexander M.|last=Polyakov|title=Particle spectrum in quantum field theory|journal=JETP Letters|volume=20|pages=194&ndash;5|year=1974|bibcode = 1974JETPL..20..194P }}</ref> Monopoles are expected to be copiously produced in Grand Unified Theories at high temperature,<ref>{{Cite journal|first=Alan|last2=Tye |last=Guth|first2=S. | title= Phase Transitions and Magnetic Monopole Production in the Very Early Universe|journal=Physical Review Letters |volume=44|issue=10|pages=631&ndash;635; Erratum ''ibid.'','''44''':963, 1980 |year=1980|doi=10.1103/PhysRevLett.44.631|bibcode = 1980PhRvL..44..631G }}</ref><ref>{{Cite journal|first=Martin B |last=Einhorn |title=Are Grand Unified Theories Compatible with Standard Cosmology?|journal=Physical Review D|volume=21|pages=3295&ndash;3298|year=1980|bibcode=1980PhRvD..21.3295E|last2=Stein|first2=D. L.|last3=Toussaint|first3=Doug|doi=10.1103/PhysRevD.21.3295|issue=12}}</ref> and they should have persisted to the present day, to such an extent that they would become the primary constituent of the universe.<ref>{{Cite journal|title=On the concentration of relic monopoles in the universe|first=Ya.|last=Zel'dovich|coauthors=M. Yu. Khlopov|year=1978|journal=Physics Letters B|volume=79|pages=239&ndash;41|bibcode=1978PhLB...79..239Z|last2=Khlopov|doi=10.1016/0370-2693(78)90232-0|issue=3}}</ref><ref>{{Cite journal|title=Cosmological production of superheavy magnetic monopoles | doi = 10.1103/PhysRevLett.43.1365|year=1979|journal=Physical Review Letters|volume=43|issue=19|pages=1365|first=John|last=Preskill|bibcode = 1979PhRvL..43.1365P }}</ref> Not only is that not the case, but all searches for them have failed, placing stringent limits on the density of relic magnetic monopoles in the universe.<ref>See, ''e.g.'' {{Cite journal|last=Yao|first=W.&ndash;M.|title=Review of Particle Physics | doi = 10.1088/0954-3899/33/1/001|journal=J. Phys. G|volume=33|issue=1|pages=1|url=http://pdg.lbl.gov/|authorlink=Particle Data Group|year=2006|arxiv = astro-ph/0601168 |bibcode = 2006JPhG...33....1Y |last2=Amsler|first2=C.|last3=Asner|first3=D.|last4=Barnett|first4=R. M.|last5=Beringer|first5=J.|last6=Burchat|first6=P. R.|last7=Carone|first7=C. D.|last8=Caso|first8=C.|last9=Dahl|first9=O.|last10=d'Ambrosio|first10=G.|last11=De Gouvea|first11=A.|last12=Doser|first12=M.|last13=Eidelman|first13=S.|last14=Feng|first14=J. L.|last15=Gherghetta|first15=T.|last16=Goodman|first16=M.|last17=Grab|first17=C.|last18=Groom|first18=D. E.|last19=Gurtu|first19=A.|last20=Hagiwara|first20=K.|last21=Hayes|first21=K. G.|last22=Hernández-Rey|first22=J. J.|last23=Hikasa|first23=K.|last24=Jawahery|first24=H.|last25=Kolda|first25=C.|last26=Kwon|first26=Y.|last27=Mangano|first27=M. L.|last28=Manohar|first28=A. V.|last29=Masoni|first29=A.|last30=Miquel|first30=R.|display-authors=29}}</ref>

A period of inflation that occurs below the temperature where magnetic monopoles can be produced would offer a possible resolution of this problem: monopoles would be separated from each other as the universe around them expands, potentially lowering their observed density by many orders of magnitude. Though, as cosmologist [[Martin Rees]] has written, "Skeptics about exotic physics might not be hugely impressed by a theoretical argument to explain the absence of particles that are themselves only hypothetical. Preventive medicine can readily seem 100 percent effective against a disease that doesn't exist!"<ref>Rees, Martin. (1998). ''Before the Beginning'' (New York: Basic Books) p. 185 ISBN 0-201-15142-1</ref>

==History==

===Precursors===

In the early days of [[General Relativity]], [[Albert Einstein]] introduced the [[cosmological constant]] to allow a [[Einstein static universe|static solution]], which was a three-dimensional sphere with a uniform density of matter. A little later, [[Willem de Sitter]] found a highly symmetric inflating universe, which described a universe with a cosmological constant that is otherwise empty.<ref>{{Cite journal|first=Willem|last=de Sitter|title=Einstein's theory of gravitation and its astronomical consequences. Third paper|journal=Monthly Notices of the Royal Astronomical Society|volume=78|pages=3&ndash;28|year=1917|bibcode = 1917MNRAS..78....3D }}</ref> It was discovered that Einstein's solution is unstable, and if there are small fluctuations, it eventually either collapses or turns into de Sitter's.

In the early 1970s [[Zeldovich]] noticed the serious flatness and horizon problems of big bang cosmology; before his work, cosmology was presumed to be symmetrical on purely philosophical grounds. In the Soviet Union, this and other considerations led Belinski and [[Khalatnikov]] to analyze the chaotic [[BKL singularity]] in General Relativity. Misner's [[Mixmaster universe]] attempted to use this chaotic behavior to solve the cosmological problems, with limited success.

In the late 1970s, [[Sidney Coleman]] applied the [[instanton]] techniques developed by [[Alexander Markovich Polyakov|Alexander Polyakov]] and collaborators to study the fate of the [[false vacuum]] in quantum field theory. Like a metastable phase in statistical mechanics&mdash;water below the freezing temperature or above the boiling point&mdash;a quantum field would need to nucleate a large enough bubble of the new vacuum, the new phase, in order to make a transition. Coleman found the most likely decay pathway for vacuum decay and calculated the inverse lifetime per unit volume. He eventually noted that gravitational effects would be significant, but he did not calculate these effects and did not apply the results to cosmology.

In the Soviet Union, [[Alexei Starobinsky]] noted that quantum corrections to general relativity should be important in the early universe. These generically lead to curvature-squared corrections to the [[Einstein&ndash;Hilbert action]] and a form of [[f(R) gravity|''f''(''R'') modified gravity]]. The solution to Einstein's equations in the presence of curvature squared terms, when the curvatures are large, leads to an effective cosmological constant. Therefore, he proposed that the early universe went through a de Sitter phase, an inflationary era.<ref>{{cite journal | author = Starobinsky, A. A. |title= Spectrum Of Relict Gravitational Radiation And The Early State Of The Universe |journal = JETP Letters|volume=30|page= 682 |year=1979 |bibcode=1979JETPL..30..682S}}; {{cite journal | bibcode = bibcode=1979ZhPmR..30..719S |journal = Pisma Zh. Eksp. Teor. Fiz.|page= 719 |year=1979 |volume=30}}</ref> This resolved the problems of cosmology, and led to specific predictions for the corrections to the microwave background radiation, corrections that were calculated in detail shortly afterwards.

In 1978, Zeldovich noted the monopole problem, which was an unambiguous quantitative version of the horizon problem, this time in a fashionable subfield of particle physics, which led to several speculative attempts to resolve it. In 1980, working in the west, [[Alan Guth]] realized that false vacuum decay in the early universe would solve the problem, leading him to propose scalar driven inflation. Starobinsky's and Guth's scenarios both predicted an initial deSitter phase, differing only in the details of the mechanism.

===Early inflationary models===

According to [[Andrei Linde]], the earliest theory of inflation was proposed by [[Erast Gliner]] (1965) but the theory was not taken seriously except by [[Andrei Sakharov]], 'who made an attempt to calculate density perturbations

produced in this scenario." <ref>{{cite journal|last=Linde|first=Andrei|title=Lectures in Inflationary Cosmology|eprint=hep-th/9410082.pdf}}</ref> Independently, inflation was proposed in January 1980 by [[Alan Guth]] as a mechanism to explain the nonexistence of magnetic monopoles.<ref name="SLAC">[[Stanford Linear Accelerator Center|SLAC]] seminar, "10<sup>−35</sup> seconds after the Big Bang", 23 January, 1980. see Guth (1997), pg 186</ref><ref name="guth">{{cite journal | doi = 10.1103/PhysRevD.23.347 | title = Inflationary universe: A possible solution to the horizon and flatness problems |url=http://www.astro.rug.nl/~weygaert/tim1publication/cosmo2007/literature/inflationary.universe.guth.physrevd-1981.pdf | format=PDF| year = 1981 | last1 = Guth | first1 = Alan H. | journal = Physical Review D | volume = 23 | issue = 2 | pages = 347–356| bibcode=1981PhRvD..23..347G }}</ref> At the same time, Starobinsky argued that quantum corrections to gravity would replace the initial singularity of the universe with an exponentially expanding deSitter phase.<ref>{{Cite journal|first=Alexei A.|last=Starobinsky|title=A new type of isotropic cosmological models without singularity|journal=Physics Letters B|volume=91|pages=99&ndash;102|year=1980 | bibcode=1980PhLB...91...99S | doi=10.1016/0370-2693(80)90670-X}}</ref> In October 1980, Demosthenes Kazanas suggested that exponential expansion could eliminate the [[particle horizon]] and perhaps solve the horizon problem,<ref>{{Cite journal|first=D.|last=Kazanas|title=Dynamics of the universe and spontaneous symmetry breaking|journal=Astrophysical Journal|volume=241|pages=L59&ndash;63|year=1980|doi=10.1086/183361|bibcode = 1980ApJ...241L..59K }}</ref> while Sato suggested that an exponential expansion could eliminate [[Domain wall (string theory)|domain walls]] (another kind of exotic relic).<ref>{{Cite journal|first=K.|last=Sato|title=Cosmological baryon number domain structure and the first order phase transition of a vacuum|journal=Physics Letters B|volume=33|pages=66&ndash;70|year=1981|bibcode=1981PhLB...99...66S|doi=10.1016/0370-2693(81)90805-4}}</ref> In 1981 Einhorn and Sato<ref>{{Cite journal|first=Martin B |last=Einhorn | title=Monopole Production In The Very Early Universe In A First Order Phase Transition|journal=Nuclear Physics B|volume=180|issue=3|pages=385&ndash;404|year=1981|doi=10.1016/0550-3213(81)90057-2|bibcode = 1981NuPhB.180..385E|last2=Sato|first2=Katsuhiko }}</ref> published a model similar to Guth's and showed that it would resolve the puzzle of the [[magnetic monopole]] abundance in [[Grand Unified Theories]]. Like Guth, they concluded that such a model not only required fine tuning of the cosmological constant, but also would very likely lead to a much too granular universe, i.e., to large density variations resulting from bubble wall collisions.

[[Image:Horizonte inflacionario.svg|thumb|right|300px|The physical size of the [[Hubble radius]] (solid line) as a function of the linear expansion (scale factor) of the universe. During cosmological inflation, the Hubble radius is constant. The physical wavelength of a perturbation mode (dashed line) is also shown. The plot illustrates how the perturbation mode grows larger than the horizon during cosmological inflation before coming back inside the horizon, which grows rapidly during radiation domination. If cosmological inflation had never happened, and radiation domination continued back until a [[gravitational singularity]], then the mode would never have been outside the horizon in the very early universe, and no [[causality (physics)|causal]] mechanism could have ensured that the universe was homogeneous on the scale of the perturbation mode.]]

Guth proposed that as the early universe cooled, it was trapped in a [[false vacuum]] with a high energy density, which is much like a [[cosmological constant]]. As the very early universe cooled it was trapped in a [[metastability|metastable]] state (it was [[supercooling|supercooled]]), which it could only decay out of through the process of [[nucleation|bubble nucleation]] via [[quantum tunneling]]. Bubbles of [[vacuum state|true vacuum]] spontaneously form in the sea of false vacuum and rapidly begin expanding at the [[speed of light]]. Guth recognized that this model was problematic because the model did not reheat properly: when the bubbles nucleated, they did not generate any radiation. Radiation could only be generated in collisions between bubble walls. But if inflation lasted long enough to solve the initial conditions problems, collisions between bubbles became exceedingly rare. In any one causal patch it is likely that only one bubble will nucleate.

===Slow-roll inflation===

The bubble collision problem was solved by [[Andrei Linde]]<ref name="linde">{{cite journal | doi = 10.1016/0370-2693(82)91219-9 | title = A new inflationary universe scenario: A possible solution of the horizon, flatness, homogeneity, isotropy and primordial monopole problems | year = 1982 | last1 = Linde | first1 = A | journal = Physics Letters B | volume = 108 | issue = 6 | pages = 389–393 | bibcode=1982PhLB..108..389L }}</ref> and independently by [[Andreas Albrecht]] and [[Paul Steinhardt]]<ref name="albrecht">{{cite journal | doi = 10.1103/PhysRevLett.48.1220 | title = Cosmology for Grand Unified Theories with Radiatively Induced Symmetry Breaking | year = 1982 | last1 = Albrecht | first1 = Andreas | last2 = Steinhardt | first2 = Paul | journal = Physical Review Letters | volume = 48 | issue = 17 | pages = 1220–1223 | bibcode=1982PhRvL..48.1220A | url=http://astrophysics.fic.uni.lodz.pl/100yrs/pdf/07/060.pdf | format=PDF }}</ref> in a model named ''new inflation'' or ''slow-roll inflation'' (Guth's model then became known as ''old inflation''). In this model, instead of tunneling out of a false vacuum state, inflation occurred by a [[scalar field]] rolling down a potential energy hill. When the field rolls very slowly compared to the expansion of the universe, inflation occurs. However, when the hill becomes steeper, inflation ends and reheating can occur.

===Effects of asymmetries===

Eventually, it was shown that new inflation does not produce a perfectly symmetric universe, but that tiny quantum fluctuations in the inflaton are created. These tiny fluctuations form the primordial seeds for all structure created in the later universe.<ref name="Hartle">{{Cite book

|author=J.B. Hartle

|year=2003

|title=Gravity: An Introduction to Einstein's General Relativity

|page=411

|edition=1st

|publisher=Addison Wesley

|isbn=0-8053-8662-9

|postscript=<!-- Bot inserted parameter. Either remove it; or change its value to "." for the cite to end in a ".", as necessary. -->{{inconsistent citations}}

}}</ref> These fluctuations were first calculated by [[Viatcheslav Mukhanov]] and G. V. Chibisov in the [[Soviet Union]] in analyzing Starobinsky's similar model.<ref>See Linde (1990) and Mukhanov (2005).</ref><ref>{{Cite journal|journal=JETP Letters|volume=33|pages=532&ndash;5|year=1981|title=Quantum fluctuation and "nonsingular" universe|first=Viatcheslav F.|last=Chibisov|bibcode = 1981JETPL..33..532M|last2=Chibisov|first2=G. V. }}</ref><ref>{{Cite journal|journal=Soviet Physics JETP|volume=56|pages=258&ndash;65|year=1982|title=The vacuum energy and large scale structure of the universe|first=Viatcheslav F.|last=Mukhanov}}</ref> In the context of inflation, they were worked out independently of the work of Mukhanov and Chibisov at the three-week 1982 Nuffield Workshop on the Very Early Universe at [[University of Cambridge|Cambridge University]].<ref>See Guth (1997) for a popular description of the workshop, or ''The Very Early Universe'', ISBN 0-521-31677-4 eds Hawking, Gibbon & Siklos for a more detailed report</ref> The fluctuations were calculated by four groups working separately over the course of the workshop: [[Stephen Hawking]];<ref>{{Cite journal|title=The development of irregularities in a single bubble inflationary universe|first=S.W.|last=Hawking|journal=Physics Letters B|volume=115|pages=295|year=1982|bibcode=1982PhLB..115..295H|doi=10.1016/0370-2693(82)90373-2|issue=4}}</ref> Starobinsky;<ref>{{Cite journal|title=Dynamics of phase transition in the new inflationary universe scenario and generation of perturbations|first=Alexei A.|last=Starobinsky|journal=Physics Letters B|volume=117|pages=175&ndash;8|year=1982|bibcode=1982PhLB..117..175S|doi=10.1016/0370-2693(82)90541-X|issue=3–4}}</ref> Guth and So-Young Pi;<ref>{{Cite journal|title=Fluctuations in the new inflationary universe|first=A.H.|last=Guth|year=1982|journal=Physical Review Letters|volume=49|issue=15|pages=1110&ndash;3|doi=10.1103/PhysRevLett.49.1110|bibcode = 1982PhRvL..49.1110G }}</ref> and [[James M. Bardeen]], [[Paul Steinhardt]] and [[Michael Turner (cosmologist)|Michael Turner]].<ref>{{Cite journal|title=Spontaneous creation Of almost scale-free density perturbations in an inflationary universe|first=James M.|last=Bardeen|journal=Physical Review D|volume=28|pages=679|year=1983|bibcode=1983PhRvD..28..679B|last2=Steinhardt|first2=Paul J.|last3=Turner|first3=Michael S.|doi=10.1103/PhysRevD.28.679|issue=4}}</ref>

==Observational status==

Inflation is a mechanism for realizing the [[cosmological principle]], which is the basis of the standard model of physical cosmology: it accounts for the homogeneity and isotropy of the observable universe. In addition, it accounts for the observed flatness and absence of magnetic monopoles. Since Guth's early work, each of these observations has received further confirmation, most impressively by the detailed observations of the [[cosmic microwave background]] made by the [[Wilkinson Microwave Anisotropy Probe]] (WMAP) spacecraft.<ref name="wmap">{{Cite journal|last=Spergel|first=D.N.|title=Three-year Wilkinson Microwave Anisotropy Probe (WMAP) observations: Implications for cosmology|url=http://lambda.gsfc.nasa.gov/product/map/current/map\_bibliography.cfm|year=2006|quote=WMAP... confirms the basic tenets of the inflationary paradigm...}}</ref> This analysis shows that the universe is flat to an accuracy of at least a few percent, and that it is homogeneous and isotropic to a part in 10,000.

In addition, inflation predicts that the structures visible in the universe today formed through the [[gravitational collapse]] of perturbations that were formed as quantum mechanical fluctuations in the inflationary epoch. The detailed form of the spectrum of perturbations called a [[scale invariance#Cosmology|nearly-scale-invariant]] [[Gaussian random field]] (or Harrison–Zel'dovich spectrum) is very specific and has only two free parameters, the amplitude of the spectrum and the ''spectral index'', which measures the slight deviation from scale invariance predicted by inflation (perfect scale invariance corresponds to the idealized de Sitter universe).<ref>Perturbations can be represented by [[Fourier modes]] of a [[wavelength]]. Each Fourier mode is [[normal distribution|normally distributed]] (usually called Gaussian) with mean zero. Different Fourier components are uncorrelated. The variance of a mode depends only on its wavelength in such a way that within any given volume each wavelength contributes an equal amount of [[spectral density|power]] to the spectrum of perturbations. Since the Fourier transform is in three dimensions, this means that the variance of a mode goes as ''k''<sup>&minus;3</sup> to compensate for the fact that within any volume, the number of modes with a given wavenumber ''k'' goes as ''k''<sup>3</sup>.</ref> Inflation predicts that the observed perturbations should be in [[thermal equilibrium]] with each other (these are called ''adiabatic'' or ''isentropic'' perturbations). This structure for the perturbations has been confirmed by the WMAP spacecraft and other cosmic microwave background experiments,<ref name="wmap" /> and [[galaxy survey]]s, especially the ongoing [[Sloan Digital Sky Survey]].<ref name="sdss">{{Cite journal|first=M.|last=Tegmark|title=Cosmological constraints from the SDSS luminous red galaxies|arxiv=astro-ph/0608632|date=August 2006|bibcode = 2006PhRvD..74l3507T |doi = 10.1103/PhysRevD.74.123507|last2=Eisenstein|first2=Daniel J.|last3=Strauss|first3=Michael A.|last4=Weinberg|first4=David H.|last5=Blanton|first5=Michael R.|last6=Frieman|first6=Joshua A.|last7=Fukugita|first7=Masataka|last8=Gunn|first8=James E.|last9=Hamilton|first9=Andrew J. S.|journal=Physical Review D|volume=74|issue=12|first10=Gillian R.|first11=Robert C.|first12=Jeremiah P.|first13=Nikhil|first14=Will J.|first15=David J.|first16=Donald P.|first17=Roman|first18=Uroš|first19=Hee-Jong|first20=Molly|first21=Alexander S.|first22=Michael S.|first23=Jaiyul|first24=Idit|first25=Kevork|first26=Scott F.|first27=James|first28=Neta A.|first29=Bruce|first30=Andreas }}</ref> These experiments have shown that the one part in 10,000 inhomogeneities observed have exactly the form predicted by theory. Moreover, there is evidence for a slight deviation from scale invariance. The ''spectral index'', ''n''<sub>s</sub> is equal to one for a scale-invariant spectrum. The simplest models of inflation predict that this quantity is between 0.92 and 0.98.<ref name="myths">{{Cite journal|title=Cosmological perturbations: Myths and facts|journal=Modern Physics Letters A|volume=19|pages=967&ndash;82|year=2004|first=Paul J.|last=Steinhardt|doi=10.1142/S0217732304014252|issue=13 & 16|bibcode = 2004MPLA...19..967S }}</ref><ref name="boyle">{{Cite journal|journal=Physical Review Letters|volume=96|year=2006|pages=111301|first=Latham A.|last=Boyle|title=Inflationary predictions for scalar and tensor fluctuations reconsidered|doi=10.1103/PhysRevLett.96.111301|pmid=16605810|last2=Steinhardt|first2=PJ|last3=Turok|first3=N|issue=11|arxiv = astro-ph/0507455 |bibcode = 2006PhRvL..96k1301B }}</ref><ref name="tegmark">{{Cite journal|first=Max|last=Tegmark|title=What does inflation really predict? | doi = 10.1088/1475-7516/2005/04/001|journal=JCAP|volume=0504|issue=4|pages=001|year=2005|arxiv=astro-ph/0410281|bibcode = 2005JCAP...04..001T }}</ref><ref>This is known as a "red" spectrum, in analogy to [[redshift]], because the spectrum has more power at longer wavelengths.</ref> From the data taken by the WMAP spacecraft it can be inferred that ''n''<sub>s</sub> = 0.963 ± 0.012,<ref>{{Cite journal|title=Seven-Year Wilkinson Microwave Anisotropy Probe (WMAP) Observations: Cosmological Interpretation|bibcode=2011ApJS..192...18K|date=January 2010|doi=10.1088/0067-0049/192/2/18|arxiv=1001.4538|last1=Komatsu|first1=E.|last2=Smith|first2=K. M.|last3=Dunkley|first3=J.|last4=Bennett|first4=C. L.|last5=Gold|first5=B.|last6=Hinshaw|first6=G.|last7=Jarosik|first7=N.|last8=Larson|first8=D.|last9=Nolta|first9=M. R.|journal=The Astrophysical Journal Supplement Series|volume=192|issue=2|pages=18|last10=Page|first10=L.|last11=Spergel|first11=D. N.|last12=Halpern|first12=M.|last13=Hill|first13=R. S.|last14=Kogut|first14=A.|last15=Limon|first15=M.|last16=Meyer|first16=S. S.|last17=Odegard|first17=N.|last18=Tucker|first18=G. S.|last19=Weiland|first19=J. L.|last20=Wollack|first20=E.|last21=Wright|first21=E. L.}}</ref> implying that it differs from one at the level of two [[standard deviation]]s (2σ). This is considered an important confirmation of the theory of inflation.<ref name="wmap" />

A number of theories of inflation have been proposed that make radically different predictions, but they generally have much more [[fine-tuning|fine tuning]] than is necessary.<ref name="myths" /><ref name="boyle" /> As a physical model, however, inflation is most valuable in that it robustly predicts the initial conditions of the universe based on only two adjustable parameters: the spectral index (that can only change in a small range) and the amplitude of the perturbations. Except in contrived models, this is true regardless of how inflation is realized in particle physics.

Occasionally, effects are observed that appear to contradict the simplest models of inflation. The first-year WMAP data suggested that the spectrum might not be nearly scale-invariant, but might instead have a slight curvature.<ref>{{Cite journal|first=D. N.|last=Spergel|url=http://www.arxiv.org/astro-ph/0302209|title=First year Wilkinson Microwave Anisotropy Probe (WMAP) observations: determination of cosmological parameters|journal=Astrophysical Journal Supplement Series|volume=148|issue=1|pages=175|year=2003|doi=10.1086/377226|last2=Verde|first2=L.|last3=Peiris|first3=H. V.|last4=Komatsu|first4=E.|last5=Nolta|first5=M. R.|last6=Bennett|first6=C. L.|last7=Halpern|first7=M.|last8=Hinshaw|first8=G.|last9=Jarosik|first9=N.|bibcode=2003ApJS..148..175S|arxiv = astro-ph/0302209|first10=A.|first11=M.|first12=S. S.|first13=L.|first14=G. S.|first15=J. L.|first16=E.|first17=E. L. }}</ref> However, the third-year data revealed that the effect was a statistical anomaly.<ref name="wmap" /> Another effect has been remarked upon since the first cosmic microwave background satellite, the [[Cosmic Background Explorer]]: the amplitude of the [[quadrupole moment]] of the cosmic microwave background is unexpectedly low and the other low multipoles appear to be preferentially aligned with the [[plane of the ecliptic|ecliptic plane]]. Some have claimed that this is a signature of non-Gaussianity and thus contradicts the simplest models of inflation. Others have suggested that the effect may be due to other new physics, foreground contamination, or even [[publication bias]].<ref>See [[cosmic microwave background#Low multipoles]] for details and references.</ref>

An experimental program is underway to further test inflation with more precise measurements of the cosmic microwave background. In particular, high precision measurements of the so-called "B-modes" of the [[Cosmic microwave background radiation#Polarization|polarization]] of the background radiation could provide evidence of the [[gravitational radiation]] produced by inflation, and could also show whether the energy scale of inflation predicted by the simplest models (10<sup>15</sup>&ndash;10<sup>16</sup> [[GeV]]) is correct.<ref name="boyle" /><ref name="tegmark" /> In March 2014, it was announced that B-mode polarization of the background radiation consistent with that predicted from inflation had been demonstrated by a South Pole experiment, a collaboration led by four principal investigators from the California Institute of Technology, Harvard University, Stanford University, and the University of Minnesota [[BICEP and Keck Array|BICEP2]].{{cn|date=March 2014}} Other potentially corroborating measurements are expected to be performed by the [[Planck (spacecraft)|Planck spacecraft]], although it is unclear if the signal will be visible, or if contamination from foreground sources will interfere with these measurements.<ref>{{Cite conference|title=Systematic effects in CMB polarization measurements|first=C.|last=Rosset|coauthors=(PLANCK-HFI collaboration)|booktitle=Exploring the universe: Contents and structures of the universe (XXXIXth Rencontres de Moriond)|year=2005}}</ref> Other forthcoming measurements, such as those of [[21 centimeter radiation]] (radiation emitted and absorbed from neutral hydrogen before the [[population III star|first stars]] turned on), may measure the power spectrum with even greater resolution than the cosmic microwave background and galaxy surveys, although it is not known if these measurements will be possible or if interference with [[radio frequency|radio sources]] on earth and in the galaxy will be too great.<ref>{{Cite journal|first=A.|last=Loeb|title=Measuring the small-scale power spectrum of cosmic density fluctuations through 21 cm tomography prior to the epoch of structure formation|journal=Physical Review Letters|volume=92|pages=211301|year=2004|arxiv=astro-ph/0312134|doi=10.1103/PhysRevLett.92.211301|pmid=15245272|last2=Zaldarriaga|first2=M|issue=21|bibcode = 2004PhRvL..92u1301L }}</ref>

[[Dark energy]] is broadly similar to inflation, and is thought to be causing the expansion of the present-day universe to accelerate. However, the energy scale of dark energy is much lower, 10<sup>−12</sup>&nbsp;GeV, roughly 27 [[orders of magnitude]] less than the scale of inflation.

==Theoretical status==

{{unsolved|physics|Is the theory of cosmological inflation correct, and if so, what are the details of this epoch? What is the hypothetical inflaton field giving rise to inflation?}}

In the early proposal of Guth, it was thought that the inflaton was the [[Higgs field]], the field that explains the mass of the elementary particles.<ref name="guth" /> It is now believed by some that the inflaton cannot be the Higgs field<ref name="guth97">{{Cite book

| last = Guth

| first = Alan

| authorlink = Alan Guth

| title = The Inflationary Universe

| publisher = [[Addison–Wesley]]

| year = 1997

| isbn = 0-201-14942-7}}</ref> although the recent discovery of the Higgs boson has increased the number of works considering the Higgs field as inflaton.{{Citation needed|date=September 2012}} Other models of inflation relied on the properties of grand unified theories.<ref name="albrecht" /> Since the simplest models of [[grand unification]] have failed, it is now thought by many physicists that inflation will be included in a [[supersymmetric]] theory like [[string theory]] or a supersymmetric grand unified theory. At present, while inflation is understood principally by its detailed predictions of the [[boundary condition|initial conditions]] for the hot early universe, the particle physics is largely ''ad hoc'' modelling. As such, though predictions of inflation have been consistent with the results of observational tests, there are many open questions about the theory.

===Fine-tuning problem===

One of the most severe challenges for inflation arises from the need for [[fine tuning]] in inflationary theories. In new inflation, the ''slow-roll conditions'' must be satisfied for inflation to occur. The slow-roll conditions say that the inflaton [[scalar potential|potential]] must be flat (compared to the large [[vacuum energy]]) and that the inflaton particles must have a small mass.<ref>Technically, these conditions are that the [[logarithmic derivative]] of the potential, <math>\epsilon=(1/2)(V'/V)^2</math> and second derivative <math>\eta=V''/V-(1/2)(V'/V)^2</math> are small, where <math>V</math> is the potential and the equations are written in [[reduced Planck units]]. See, ''e.g.'' Liddle and Lyth (2000).</ref> In order for the new inflation theory of Linde, Albrecht and Steinhardt to be successful, therefore, it seemed that the universe must have a scalar field with an especially flat potential and special initial conditions.

====[[Andrei Linde]]====

Andrei Linde proposed a theory known as ''[[Chaotic inflation theory|chaotic inflation]]'' in which he suggested that the conditions for inflation are actually satisfied quite generically and inflation will occur in virtually [[Multiverse|any universe]] that begins in a chaotic, high energy state and has a scalar field with unbounded potential energy.<ref name="chaotic">{{Cite journal|first=Andrei D.|last=Linde|title=Chaotic inflation|doi=10.1016/0370-2693(83)90837-7|journal=Physics Letters B|volume=129|issue=3|pages=171&ndash;81|year=1983 }}</ref> However, in his model the inflaton field necessarily takes values larger than one [[Planck unit]]: for this reason, these are often called ''large field'' models and the competing new inflation models are called ''small field'' models. In this situation, the predictions of [[effective field theory]] are thought to be invalid, as [[renormalization]] should cause large corrections that could prevent inflation.<ref>Technically, this is because the inflaton potential is expressed as a Taylor series in φ/''m''<sub>Pl</sub>, where φ is the inflaton and ''m''<sub>Pl</sub> is the Planck mass. While for a single term, such as the mass term ''m''<sub>φ</sub><sup>4</sup>(φ/''m''<sub>Pl</sub>)<sup>2</sup>, the slow roll conditions can be satisfied for φ much greater than ''m''<sub>Pl</sub>, this is precisely the situation in effective field theory in which higher order terms would be expected to contribute and destroy the conditions for inflation. The absence of these higher order corrections can be seen as another sort of fine tuning. See ''e.g.'' {{Cite journal|first=Laila|last=Alabidi|title=Inflation models and observation | doi = 10.1088/1475-7516/2006/05/016|journal=JCAP|volume=0605|issue=5|year=2006|pages=016|arxiv=astro-ph/0510441|last2=Lyth|first2=David H|bibcode = 2006JCAP...05..016A }}</ref> This problem has not yet been resolved and some cosmologists argue that the small field models, in which inflation can occur at a much lower energy scale, are better models of inflation.<ref>See, ''e.g.'' {{Cite journal|title=What would we learn by detecting a gravitational wave signal in the cosmic microwave background anisotropy? | doi = 10.1103/PhysRevLett.78.1861|first=David H.|last=Lyth|journal=Physical Review Letters|volume=78|issue=10|pages=1861&ndash;3|year=1997|arxiv=hep-ph/9606387|url=http://www.slac.stanford.edu/spires/find/hep/www?rawcmd=FIND+EPRINT+HEP-PH/9606387|bibcode = 1997PhRvL..78.1861L }}</ref> While inflation depends on quantum field theory (and the [[semiclassical gravity|semiclassical approximation]] to [[quantum gravity]]) in an important way, it has not been completely reconciled with these theories. The [[BICEP2]] experiment detected evidence for primordial [[gravitational wave]]s consistent with Linde's model.

[[Robert Brandenberger]] has commented on fine-tuning in another situation.<ref>{{Cite conference|title=Challenges for inflationary cosmology|first=Robert H.|last=Brandenberger|date=November 2004|booktitle=10th International Symposium on Particles, Strings and Cosmology|arxiv=astro-ph/0411671}}</ref> The amplitude of the primordial inhomogeneities produced in inflation is directly tied to the energy scale of inflation. There are strong suggestions that this scale is around 10<sup>16</sup> [[GeV]] or 10<sup>&minus;3</sup> times the [[Planck energy]]. The natural scale is naïvely the Planck scale so this small value could be seen as another form of fine-tuning (called a [[hierarchy problem]]): the energy density given by the scalar potential is down by 10<sup>&minus;12</sup> compared to the [[Planck density]]. This is not usually considered to be a critical problem, however, because the scale of inflation corresponds naturally to the scale of gauge unification.

===Eternal inflation===

{{Main|Eternal inflation}}

In many models of inflation, the inflationary phase of the universe's expansion lasts forever in at least some regions of the universe. This occurs because inflating regions expand very rapidly, reproducing themselves. Unless the rate of decay to the non-inflating phase is sufficiently fast, new inflating regions are produced more rapidly than non-inflating regions. In such models most of the volume of the universe at any given time is inflating. All models of eternal inflation produce an infinite multiverse, typically a fractal.

Although new inflation is classically rolling down the potential, quantum fluctuations can sometimes bring it back up to previous levels. These regions in which the inflaton fluctuates upwards expand much faster than regions in which the inflaton has a lower potential energy, and tend to dominate in terms of physical volume. This steady state, which first developed by Vilenkin,<ref name="vilenkin">{{Cite journal|first=Alexander|last=Vilenkin|title=The birth of inflationary universes | doi = 10.1103/PhysRevD.27.2848|journal=Physical Review D|volume=27|issue=12|pages=2848|year=1983|bibcode = 1983PhRvD..27.2848V }}</ref> is called "eternal inflation". It has been shown that any inflationary theory with an unbounded potential is eternal.<ref>{{Cite journal| author = A. Linde |title = Eternal chaotic inflation | journal = Modern Physics Letters A |volume = 1 |year =1986 | pages=81 | doi=10.1142/S0217732386000129|bibcode = 1986MPLA....1...81L| issue = 2 }} {{Cite journal| author = A. Linde |title = Eternally existing self-reproducing chaotic inflationary universe |url=http://www.stanford.edu/~alinde/Eternal86.pdf| journal = Physics Letters B|volume = 175 |year =1986|pages=395&ndash;400 |doi=10.1016/0370-2693(86)90611-8|bibcode = 1986PhLB..175..395L| issue = 4 }}</ref>{{Failed verification|date=March 2013}} It is a popular conclusion among physicists that this steady state cannot continue forever into the past.<ref>{{Cite journal|author = A. Borde, A. Guth and A. Vilenkin |title = Inflationary space-times are incomplete in past directions|journal = Physical Review Letters|volume=90|year=2003|pages=151301 |doi = 10.1103/PhysRevLett.90.151301 |pmid = 12732026 |issue = 15|arxiv = gr-qc/0110012 |bibcode = 2003PhRvL..90o1301B }}</ref><ref>{{Cite journal|author = A. Borde |title = Open and closed universes, initial singularities and inflation|journal = Physical Review D|volume=50|year=1994|pages=3692&ndash;702|bibcode = 1994PhRvD..50.3692B|doi = 10.1103/PhysRevD.50.3692|issue = 6}}</ref><ref>{{Cite journal|author = A. Borde and A. Vilenkin |title = Eternal inflation and the initial singularity|journal = Physical Review Letters|volume=72|year=1994|issue = 21|pages=3305&ndash;9 |doi = 10.1103/PhysRevLett.72.3305|arxiv = gr-qc/9312022 |bibcode = 1994PhRvL..72.3305B }}</ref> The inflationary spacetime, which is similar to [[de Sitter space]], is incomplete without a contracting region. However, unlike de Sitter space, fluctuations in a contracting inflationary space will collapse to form a [[gravitational singularity]], a point where densities become infinite. Therefore, it is necessary to have a theory for the universe's initial conditions. Linde, however, believes inflation may be past eternal.<ref>Linde (2005, §V).</ref>

In eternal inflation, regions with inflation have an exponentially growing volume, while regions that are not inflating don't. This suggests that the volume of the inflating part of the universe in the global picture is always unimaginably larger than the part that has stopped inflating, even though inflation eventually ends as seen by any single pre-inflationary observer. Scientists disagree about how to assign a probability distribution to this hypothetical [[anthropic landscape]]. If the probability of different regions is counted by volume, one should expect that inflation will never end, or applying boundary conditions that a local observer exists to observe it, that inflation will end as late as possible. Some physicists believe this paradox can be resolved by weighting observers by their pre-inflationary volume.

===Initial conditions===

Some physicists have tried to avoid the initial conditions problem by proposing models for an eternally inflating universe with no origin.<ref>{{Cite journal|title=Does inflation provide natural initial conditions for the universe?|first=Sean M.|last=Carroll|journal=Gen. Rel. Grav.|volume=37|issue=10|pages=1671&ndash;4|year=2005|arxiv=gr-qc/0505037|doi=10.1007/s10714-005-0148-2|last2=Chen|first2=Jennifer|bibcode = 2005GReGr..37.1671C }}</ref><ref>{{cite arXiv|title=Spontaneous inflation and the origin of the arrow of time|first=Sean M.|last=Carroll|eprint=hep-th/0410270|bibcode = 2004hep.th...10270C|author2=Jennifer Chen|class=hep-th|year=2004 }}</ref><ref>{{cite journal | first1=Anthony |last1=Aguirre|first2= Steven |last2=Gratton|title=Inflation without a beginning: A null boundary proposal| journal= Physical Review D | volume=67 |year=2003|page= 083515|arxiv=gr-qc/0301042|doi=10.1103/PhysRevD.67.083515 | issue=8 |bibcode = 2003PhRvD..67h3515A }}</ref><ref>{{cite journal | first1=Anthony |last1=Aguirre|first2= Steven |last2=Gratton|title=Steady-State Eternal Inflation|journal= Physical Review D |volume=65 |year=2002|page= 083507|arxiv=astro-ph/0111191 |bibcode = 2002PhRvD..65h3507A |doi = 10.1103/PhysRevD.65.083507 | issue=8 }}</ref> These models propose that while the universe, on the largest scales, expands exponentially it was, is and always will be, spatially infinite and has existed, and will exist, forever.

Other proposals attempt to describe the ex nihilo creation of the universe based on [[quantum cosmology]] and the following inflation. Vilenkin put forth one such scenario.<ref name="vilenkin" /> Hartle and Hawking offered the [[no-boundary proposal]] for the initial creation of the universe in which inflation comes about naturally.<ref>{{cite journal | doi = 10.1103/PhysRevD.28.2960| title=Wave function of the universe | year = 1983 | last1 = Hartle | first1 = J. | last2 = Hawking | first2 = S. | journal = Physical Review D | volume = 28 | issue = 12 | pages = 2960 |bibcode = 1983PhRvD..28.2960H }}; See also Hawking (1998).</ref>

[[Alan Guth]] has described the inflationary universe as the "ultimate free lunch":<ref>Hawking (1998), p. 129.</ref><ref>[[q:Alan Guth|Wikiquote]]</ref> new universes, similar to our own, are continually produced in a vast inflating background. Gravitational interactions, in this case, circumvent (but do not violate) the [[first law of thermodynamics]] ([[energy conservation]]) and the [[second law of thermodynamics]] ([[entropy]] and the [[arrow of time]] problem). However, while there is consensus that this solves the initial conditions problem, some have disputed this, as it is much more likely that the universe came about by a [[quantum fluctuation]]. [[Don Page (physicist)|Donald Page]] was an outspoken critic of inflation because of this anomaly.<ref>{{cite journal | title=Inflation does not explain time asymmetry| bibcode=1983Natur.304...39P | doi=10.1038/304039a0 | year=1983 | last1=Page | first1=Don N. | journal=Nature | volume=304 | issue=5921 | pages=39}}; see also [[Roger Penrose]]'s book [[The Road to Reality: A Complete Guide to the Laws of the Universe]].</ref> He stressed that the thermodynamic [[arrow of time]] necessitates low [[entropy]] initial conditions, which would be highly unlikely. According to them, rather than solving this problem, the inflation theory further aggravates it &ndash; the reheating at the end of the inflation era increases entropy, making it necessary for the initial state of the Universe to be even more orderly than in other Big Bang theories with no inflation phase.

Hawking and Page later found ambiguous results when they attempted to compute the probability of inflation in the Hartle-Hawking initial state.<ref>{{Cite journal|title=How probable is inflation?|first=S. W.|last=Hawking|year=1988|volume=298|issue=4|pages=789|journal=Nuclear Physics B|doi=10.1016/0550-3213(88)90008-9|bibcode = 1988NuPhB.298..789H|last2=Page|first2=Don N. }}</ref> Other authors have argued that, since inflation is eternal, the probability doesn't matter as long as it is not precisely zero: once it starts, inflation perpetuates itself and quickly dominates the universe.{{Citation needed|date=February 2007}} However, Albrecht and Lorenzo Sorbo have argued that the probability of an inflationary cosmos, consistent with today's observations, emerging by a random fluctuation from some pre-existent state, ''compared'' with a non-inflationary cosmos overwhelmingly favours the inflationary scenario, simply because the "seed" amount of non-gravitational energy required for the inflationary cosmos is so much less than any required for a non-inflationary alternative, which outweighs any entropic considerations.<ref>{{Cite journal|first=Andreas|last=Albrecht|title=Can the universe afford inflation?|journal=Physical Review D|volume=70|pages=063528|year=2004|arxiv=hep-th/0405270|bibcode = 2004PhRvD..70f3528A |doi = 10.1103/PhysRevD.70.063528|last2=Sorbo|first2=Lorenzo|issue=6 }}</ref>

Another problem that has occasionally been mentioned is the trans-Planckian problem or trans-Planckian effects.<ref>{{Cite journal|first=Jerome|last2=Brandenberger|last=Martin|first2=Robert|title=The trans-Planckian problem of inflationary cosmology|journal=Physical Review D|volume=63|year=2001|issue=12|pages=123501|arxiv=hep-th/0005209|doi=10.1103/PhysRevD.63.123501|bibcode = 2001PhRvD..63l3501M }}</ref> Since the energy scale of inflation and the Planck scale are relatively close, some of the quantum fluctuations that have made up the structure in our universe were smaller than the Planck length before inflation. Therefore, there ought to be corrections from Planck-scale physics, in particular the unknown quantum theory of gravity. There has been some disagreement about the magnitude of this effect: about whether it is just on the threshold of detectability or completely undetectable.<ref>{{Cite journal|first=Jerome|last=Martin|title=Superimposed Oscillations in the WMAP Data?|journal=Physical Review D|volume=69|issue=8|year=2004|pages=083515|arxiv=astro-ph/0310382|doi=10.1103/PhysRevD.69.083515|last2=Ringeval|first2=Christophe|bibcode = 2004PhRvD..69h3515M }}</ref>

===Hybrid inflation===

Another kind of inflation, called ''hybrid inflation'', is an extension of new inflation. It introduces additional scalar fields, so that while one of the scalar fields is responsible for normal slow roll inflation, another triggers the end of inflation: when inflation has continued for sufficiently long, it becomes favorable to the second field to decay into a much lower energy state.<ref>Robert H. Brandenberger, "A Status Review of Inflationary Cosmology", proceedings

Journal-ref: BROWN-HET-1256 (2001), (available from {{arxiv|hep-ph/0101119v1}} 11 January 2001)</ref>

In hybrid inflation, one of the scalar fields is responsible for most of the energy density (thus determining the rate of expansion), while the other is responsible for the slow roll (thus determining the period of inflation and its termination). Thus fluctuations in the former inflaton would not affect inflation termination, while fluctuations in the latter would not affect the rate of expansion. Therefore hybrid inflation is not eternal.<ref>Andrei Linde, "Prospects of Inflation", ''Physica Scripta Online'' (2004) (available from {{arxiv|hep-th/0402051}} )</ref><ref>Blanco-Pillado et al., "Racetrack inflation", (2004) (available from {{arxiv|hep-th/0406230}} )</ref> When the second (slow-rolling) inflaton reaches the bottom of its potential, it changes the location of the minimum of the first inflaton's potential, which leads to a fast roll of the inflaton down its potential, leading to termination of inflation.

===Inflation and string cosmology===

The discovery of [[Compactification (physics)#Flux compactification|flux compactification]]s have opened the way for reconciling inflation and string theory.<ref>{{Cite journal|title=Towards inflation in string theory|first=Shamit|last=Kachru|year=2003|journal=JCAP|volume=0310|pages=013|arxiv=hep-th/0308055|bibcode = 2003JCAP...10..013K |doi = 10.1088/1475-7516/2003/10/013|last2=Kallosh|first2=Renata|last3=Linde|first3=Andrei|last4=Maldacena|first4=Juan|last5=McAllister|first5=Liam|last6=Trivedi|first6=Sandip P|issue=10 }}</ref> A new theory, called ''brane inflation'' suggests that inflation arises from the motion of [[D-brane]]s<ref>G. R. Dvali, S. H. Henry Tye, ''Brane inflation,'' ''Phys.Lett.'' '''B450''', 72-82 (1999), {{arxiv|hep-ph/9812483}}.</ref> in the compactified geometry, usually towards a stack of anti-D-branes. This theory, governed by the ''Dirac-Born-Infeld action'', is very different from ordinary inflation. The dynamics are not completely understood. It appears that special conditions are necessary since inflation occurs in tunneling between two vacua in the [[string landscape]]. The process of tunneling between two vacua is a form of old inflation, but new inflation must then occur by some other mechanism.

===Inflation and loop quantum gravity===

When investigating the effects the theory of [[loop quantum gravity]] would have on cosmology, a [[loop quantum cosmology]] model has evolved that provides a possible mechanism for cosmological inflation. Loop quantum gravity assumes a quantized spacetime. If the energy density is larger than can be held by the quantized spacetime, it is thought to bounce back. <!-- Scientfic American October 2008, see also [[loop quantum cosmology]] -->

===Inflation and generalized uncertainty principle (GUP)===

The effects of generalized uncertainty principle (GUP) on the inflationary dynamics and the thermodynamics of the [[early Universe]] are studied.<ref>A. Tawfik, H. Magdy and A. Farag Ali, [http://link.springer.com/article/10.1007%2Fs10714-013-1522-0 Gen.Rel.Grav. 45 (2013) 1227-1246]</ref> Using the GUP approach, [http://atawfik.net/ Tawfik] et al. evaluated the tensorial and scalar density fluctuations in the inflation era and compared them with the standard case. They found a good agreement with the [[Wilkinson Microwave Anisotropy Probe]] data. Assuming that a quantum gas of scalar particles is confined within a thin layer near the apparent horizon of the [[Friedmann-Lemaitre-Robertson-Walker]] Universe that satisfies the boundary condition, [http://atawfik.net/ Tawfik] et al. calculated the number and entropy densities and the free energy arising from the quantum states using the GUP approach. Furthermore, a qualitative estimation for effects of the quantum gravity on all these thermodynamic quantities was introduced.

==Alternatives to inflation==

The flatness and horizon problems are naturally solved in the [[Einstein–Cartan theory|Einstein-Cartan]]-Sciama-Kibble theory of gravity, without needing an exotic form of matter and introducing free parameters.<ref>{{cite journal |author=Poplawski, N. J. |year=2010 |title=Cosmology with torsion: An alternative to cosmic inflation| journal=Physics Letters B |volume=694 |issue=3 |pages=181–185 |doi=10.1016/j.physletb.2010.09.056|arxiv = 1007.0587 |bibcode = 2010PhLB..694..181P }}</ref><ref>{{cite journal |author=Poplawski, N. |year=2012 |title=Nonsingular, big-bounce cosmology from spinor-torsion coupling |journal=Physical Review D |volume=85 |issue=10 |pages=107502 |doi=10.1103/PhysRevD.85.107502|arxiv = 1111.4595 |bibcode = 2012PhRvD..85j7502P }}</ref> This theory extends general relativity by removing a constraint of the symmetry of the affine connection and regarding its antisymmetric part, the [[torsion tensor]], as a dynamical variable. The minimal coupling between torsion and Dirac spinors generates a spin-spin interaction that is significant in fermionic matter at extremely high densities. Such an interaction averts the unphysical Big Bang singularity, replacing it with a cusp-like bounce at a finite minimum scale factor, before which the Universe was contracting. The rapid expansion immediately after the [[Big Bounce]] explains why the present Universe at largest scales appears spatially flat, homogeneous and isotropic. As the density of the Universe decreases, the effects of torsion weaken and the Universe smoothly enters the radiation-dominated era.

There are models that explain some of the observations explained by inflation. However none of these "alternatives" has the same breadth of explanation as inflation, and still require inflation for a more complete fit with observation; they should therefore be regarded as adjuncts to inflation, rather than as alternatives.

[[String theory]] requires that, in addition to the three observable spatial dimensions, there exist additional dimensions that are curled up or [[compactification (physics)|compactified]] (see also [[Kaluza–Klein theory]]). Extra dimensions appear as a frequent component of [[supergravity]] models and other approaches to [[quantum gravity]]. This raised the contingent question of why four space-time dimensions became large and the rest became unobservably small. An attempt to address this question, called ''string gas cosmology'', was proposed by [[Robert Brandenberger]] and [[Cumrun Vafa]].<ref>{{cite journal | doi = 10.1016/0550-3213(89)90037-0 | title = Superstrings in the early universe | year = 1989 | last1 = Brandenberger | first1 = R | journal = Nuclear Physics B | volume = 316 | issue = 2 | pages = 391–410 | bibcode=1989NuPhB.316..391B | last2 = Vafa | first2 = C. }}</ref> This model focuses on the dynamics of the early universe considered as a hot gas of strings. Brandenberger and Vafa show that a dimension of [[spacetime]] can only expand if the strings that wind around it can efficiently annihilate each other. Each string is a one-dimensional object, and the largest number of dimensions in which two strings will [[Transversality (mathematics)|generically intersect]] (and, presumably, annihilate) is three. Therefore, one argues that the most likely number of non-compact (large) spatial dimensions is three. Current work on this model centers on whether it can succeed in stabilizing the size of the compactified dimensions and produce the correct spectrum of primordial density perturbations. For a recent review, see<ref>{{cite journal | first1=Thorsten |last1=Battefeld |first2= Scott |last2=Watson|title= String Gas Cosmology | journal = Reviews Modern Physics|volume=78|pages= 435–454 |year=2006|arxiv=hep-th/0510022|doi=10.1103/RevModPhys.78.435|bibcode = 2006RvMP...78..435B | issue=2 }}</ref> The authors admits that their model "does not solve the entropy and flatness problems of standard cosmology ..... and we can provide no explanation for why the current universe is so close to being spatially flat".<ref>{{cite journal | first=Robert H. |last=Brandenberger|title=String Gas Cosmology and Structure Formation|journal= International Journal of Modern Physics A|volume=22|pages=3621–3642|year=2007|arxiv=hep-th/0608121|doi=10.1142/S0217751X07037159|bibcode = 2007IJMPA..22.3621B | first2=ALI |last3=Patil| first3=Subodh P. |last4=Vafa| first4=Cumrun | issue=21 |last2=Nayeri}}</ref>

The [[ekpyrotic]] and [[cyclic model]]s are also considered adjuncts to inflation. These models solve the [[horizon problem]] through an expanding epoch well ''before'' the Big Bang, and then generate the required spectrum of primordial density perturbations during a contracting phase leading to a [[Big Crunch]]. The universe passes through the Big Crunch and emerges in a hot [[Big Bang]] phase. In this sense they are reminiscent of the [[oscillatory universe]] proposed by [[Richard Chace Tolman]]: however in Tolman's model the total age of the universe is necessarily finite, while in these models this is not necessarily so. Whether the correct spectrum of density fluctuations can be produced, and whether the universe can successfully navigate the Big Bang/Big Crunch transition, remains a topic of controversy and current research. Ekpyrotic models avoid the [[magnetic monopole]] problem as long as the temperature at the Big Crunch/Big Bang transition remains below the Grand Unified Scale, as this is the temperature required to produce magnetic monopoles in the first place. As things stand, there is no evidence of any 'slowing down' of the expansion, but this is not surprising as each cycle is expected to last on the order of a trillion years.

Another adjunct, the [[varying speed of light]] model has also been theorized by [[Jean-Pierre Petit]] in 1988, [[John Moffat (physicist)|John Moffat]] in 1992 as well [[Andreas Albrecht]] and [[João Magueijo]] in 1999, instead of superluminal expansion the speed of light was 60 orders of magnitude faster than its current value solving the horizon and homogeneity problems in the early universe.

==Criticisms==

Since its introduction by Alan Guth in 1980, the inflationary paradigm has become widely accepted. Nevertheless, many physicists, mathematicians, and philosophers of science have voiced criticisms, claiming unfulfilled promises and an alleged lack of serious empirical support.{{cn|reason=Would need a more recent, post-1999 cite for claim that inflation lacks serious empirical support if we want to retain this claim|date=January 2014}} In 1999, John Earman and Jesús Mosterín published a thorough critical review of inflationary cosmology, concluding, "we do not think that there are, as yet, good grounds for admitting any of the models of inflation into the standard core of cosmology."<ref>{{cite journal | last1=Earman|first1= John |first2=Jesús |last2=Mosterín |date=March 1999|title=A Critical Look at Inflationary Cosmology| journal= Philosophy of Science |volume=66 |pages= 1–49 |doi=10.2307/188736 |jstor=188736|doi\_brokendate= 2014-03-25 }}</ref>

In order to work, and as pointed out by [[Roger Penrose]] from 1986 on, inflation requires extremely specific initial conditions of its own, so that the problem (or pseudo-problem) of initial conditions is not solved: "There is something fundamentally misconceived about trying to explain the uniformity of the early universe as resulting from a thermalization process. [...] For, if the thermalization is actually doing anything [...] then it represents a definite increasing of the entropy. Thus, the universe would have been even more special before the thermalization than after."<ref>Penrose, Roger (2004). ''The Road to Reality: A Complete Guide to the Laws of the Universe''. London: Vintage Books, p. 755. See also {{cite journal | last=Penrose|first= Roger |year=1989|title=Difficulties with Inflationary Cosmology| journal=Annals of the New York Academy of Sciences|volume= 271|pages= 249–264|bibcode=1989NYASA.571..249P |doi = 10.1111/j.1749-6632.1989.tb50513.x }}</ref> The problem of specific or "fine-tuned" initial conditions would not have been solved; it would have gotten worse.

A recurrent criticism of inflation is that the invoked inflation field does not correspond to any known physical field, and that its [[potential energy]] curve seems to be an ad hoc contrivance to accommodate almost any data obtainable. [[Paul J. Steinhardt]], one of the founding fathers of inflationary cosmology, has recently become one of its sharpest critics. He calls 'bad inflation' a period of accelerated expansion whose outcome conflicts with observations, and 'good inflation' one compatible with them: "Not only is bad inflation more likely than good inflation, but no inflation is more likely than either.... Roger Penrose considered all the possible configurations of the inflaton and gravitational fields. Some of these configurations lead to inflation ... Other configurations lead to a uniform, flat universe directly – without inflation. Obtaining a flat universe is unlikely overall. Penrose's shocking conclusion, though, was that obtaining a flat universe without inflation is much more likely than with inflation – by a factor of 10 to the googol (10 to the 100) power!"<ref>Steinhardt, Paul J. (2011). "The inflation debate: Is the theory at the heart of modern cosmology deeply flawed?" (''Scientific American'', April; pp. 18-25). See also: Steinhardt, Paul J. and Neil Turok (2007). ''Endless Universe: Beyond the Big Bang''. Doubleday, 2007.</ref>

==參見==

\* [[膜宇宙學]]

\* [[宇宙學]]

\* [[哈勃定律]]

\* [[非線性光學]]

\* [[光速可變理論]]

==註釋==

{{Reflist|group="注"}}

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\* [http://www2.iap.fr/Conferences/Colloque/col2004/Docs/20040628\_liddle.pdf update 2004] by Andrew Liddle

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