

8.9: Historical Note - The Steady-state Model

From 1948 until around the mid-1960s, the [Big Bang theory](#) had viable competition in the form of the steady-state model, originated by the British trio of Fred Hoyle, Hermann Bondi, and Thomas Gold. Legend has it that they came up with the idea after seeing a horror movie called *Dead of Night*, in which events from the beginning of the story repeat themselves later. This led them to imagine that the universe could, although expanding, remain locally in the same state at all times. If this were to happen, the empty space being opened up between the galaxies would have to be filled back in by the spontaneous creation of matter. The model holds a strong philosophical appeal because it generalizes the Copernican principle so that it applies not just to conditions everywhere in space but also at all times.

They published the idea in a pair of back-to-back papers, one by Bondi and Gold³⁹ and one by Hoyle,⁴⁰ with comments appended to the former on the differences between the two approaches. The Bondi-Gold paper is especially fun to read, because it is written in nontechnical language and shows a type of daring and creative science that is not often encountered today. Much of it reads like a catalog of cherished principles of physics that were to be given up, including Lorentz invariance, general relativity, the equivalence principle, and possibly the laws of conservation of charge and mass-energy. The following is a brief presentation (in slightly different notation) of the Hoyle's more mathematically detailed ideas, as sketched in his original paper. Although Hoyle eventually fleshed out the ideas more thoroughly, by the time he had done so the steady-state theory was already on its way to being crushed under the weight of contrary observations.

Since the model is always to be in the same state, the quantity $\frac{\dot{a}}{a}$ must always be the same, i.e., the Hubble constant really is a constant over time. This requires exponential growth, which means that the geometry is that of de Sitter space. In any model that assigns an infinite age to the universe, one must explain why the universe has not undergone heat death due to the second law of thermodynamics. The steady-state model successfully addresses this problem, because the exponential expansion is rapid enough to prevent thermal equilibrium from happening.

Hoyle sets out to preserve local conservation of energy-momentum, without which the Einstein field equations become inconsistent. (This was Hoyle's more conservative approach. Bondi and Gold advocated replacing general relativity completely rather than modifying it.) He postulates a massless, chargeless, scalar field C , called the "C field," the letter "C" standing for "creation." Suppose that the C field's contribution to the stress-energy tensor ends up being that of a perfect fluid with the same rest frame as the ordinary matter. The rate of creation of mass-energy is then given by the divergence $\nabla_\mu T_t^\mu$, and we need this to be zero. As shown in [example 21](#), this requires that our total stress-energy mimic that of a cosmological constant, with $\rho + P = 0$. Since the ordinary matter has $\rho > 0$ and $P > 0$, the C field will either need to contribute negative energy density or negative pressure. We'll see below that Hoyle's model is constructed so that the C field has zero energy and negative pressure. One will often see the C field described incorrectly as having negative energy to cancel out the positive energy of the matter being created. That wouldn't have worked, because then the total energy density ρ would always be zero, which is not what we observe. (For example, the Friedmann equation for $\frac{\dot{a}}{a}$ relates ρ to the square of the Hubble constant.)

To understand more about why the theory took the form it did, it is helpful to look at some general physical considerations about symmetry. As Bondi and Gold admit candidly, any theory of this type is likely to violate Lorentz invariance. We can observe an evacuated box and wait for hydrogen atoms to appear. When they appear, they're in some state of motion, at least on the average. This state of motion defines a preferred frame. In addition to breaking symmetry under Lorentz transformations, the theory lacks timereversal invariance (because matter appears but never disappears) and charge-conjugation symmetry (because matter appears but antimatter doesn't). All of these asymmetries arise because in this approach, we try to explain the observed asymmetries of the cosmological state of the universe as arising directly from asymmetries in the underlying local laws of physics. Such an approach is very different from the modern one, in which we expect the asymmetries to arise from either boundary conditions or instabilities (spontaneous symmetry breaking).

Because the C field is massless and chargeless, we would normally expect it to obey the wave equation $\nabla_a \nabla^a C = 0$. Hoyle's field does not, however, evolve according to any Lorentz-invariant dynamical law. Instead it simply evolves as $C = t$, where t is a preferred time coordinate. In any cosmological model in which the matter fields are modeled as perfect fluids, we have a preferred time coordinate which is the proper time of an observer at rest with respect to the fluid, and in the Hoyle model we do assume that this is the time t we should use in defining C . However, Hoyle's theory is different because it gives this preferred time a role in the local laws of physics, thereby breaking Lorentz invariance.

The value of the scalar field C cannot have any directly observable effects, since then its time-evolution would distinguish one epoch of the universe from another. Instead we form the gradient $\nabla_a C$. This gives a vector, which can be interpreted as a velocity

vector defining the preferred frame of reference. An observer in this frame is at rest relative to the local cosmological fluid, observes the universe to be homogeneous, and also observes that when new atoms are created from the vacuum, they are on the average at rest. Thus $\nabla_a C$ is observable.

The contribution of the C field to the stress-energy must be a rank-two tensor, and if we want to construct such a tensor, the only good possibility that occurs to me⁴¹ is $k\nabla_a\nabla_b C$, with k a positive constant. If the derivatives had been ordinary partial derivatives, the second derivative would have vanished because C is linear in time, but the covariant derivatives do not vanish, and in fact the second derivative is a tensor measuring the rate of cosmological expansion; the trace $\nabla^a\nabla_a C$ is the volume expansion Θ defined in [section 8.1](#). For de Sitter space, Θ has a constant value equal to three times the Hubble constant H_0 . We can now see why we could not take the C field to evolve according to the usual wave equation $\nabla_a\nabla^a C = 0$; if it did, then we would have $\Theta = 0$, and the universe would not be expanding.

Note

The only other obvious possibility would have been something like $-k\nabla_a C\nabla_b C$. This would be the stress-energy of a negative-mass dust, which would be unacceptable for the reasons discussed earlier.

When we evaluate the second derivative for the de Sitter metric, the only nonvanishing Christoffel symbols that occur are

$$\Gamma_{xx}^t = \Gamma_{yy}^t = \Gamma_{zz}^t = \dot{a}a. \quad (8.9.1)$$

We find

$$T_t^t = 0 \quad (8.9.2)$$

and

$$T_x^x = T_y^y = T_z^z = \frac{k\Theta}{3}. \quad (8.9.3)$$

Thus the C field's mass-energy density is zero, while for its pressure we have $P = -\frac{k\Theta}{3}$, which is negative.

For simplicity, we take the ordinary matter to be dust. The total stress-energy then consists of an energy density ρ that is due only to the dust, and a negative pressure P that comes only from the C field. If we require both of these to be constant, take the cosmological constant to be zero, set

$$a = e^{H_0 t} = e^{\Theta t/3} \quad (8.9.4)$$

and substitute into the [Friedmann equations](#) from [Section 8.2](#), we find $P = -\rho$, or

$$k = \frac{3\rho}{\Theta} = \frac{\rho}{H_0}. \quad (8.9.5)$$

Like the cosmological constant, the C field is taken to be a universally prescribed property of the vacuum. There is a difference, however, because the cosmological constant's contribution to the stress-energy is proportional to the metric, which preserves the equivalence principle. As remarked at the end of the Bondi-Gold paper, the C field violates the equivalence principle. No calculation is spelled out, but they say based on a personal communication from Hoyle that the field exerts a force on matter which produces a significant acceleration in an atom, but a negligible one in a star.

A claimed selling point of the C field was that it would prevent the formation of singularities, including both a Big Bang singularity and black holes. This is reasonable, since the C field violates all of the energy conditions listed in [section 8.1](#) except for the trace energy condition. The Penrose singularity theorem depends on the null energy condition, and the Hawking singularity theorem requires either the strong or the null energy condition.

Because we can't make the C field obey the proper wave equation for a massless, spin-zero particle, there is no obvious way to make up a dynamical law for its evolution in order to replace the fixed relation $C = t$, and we do not expect to have any classical field theory for the C field. Hoyle did attempt to add dynamics to the model by making it into what is known as a "direct field," which was a type of action-at-a-distance theory that in the 1960s was believed to be a good candidate for the fundamental description of the forces of physics. (Quantum field theory had not developed to the point where it could handle the strong or weak nuclear forces.) Such theories were shown to be nonviable as quantum theories in 1963 by Currie, Jordan, and Sudarshan.

The steady-state model began to succumb to contrary evidence when Ryle and coworkers counted radio sources and found that they did not show the statistical behavior predicted by the model. The coup de grace came with the discovery of the cosmic microwave background, which demonstrated directly that the universe had once been much hotter than it is now. Attempts have been made to produce variations on the model that are consistent with these observations, but they have not succeeded; for a detailed discussion see <http://www.astro.ucla.edu/~wright/stdystat.htm>.

References

³⁹ “The Steady-State Theory of the Expanding Universe,” MNRAS 108 (1948) 252; adsabs.harvard.edu/cgi-bin/nph-bib_query?bibcode=1948MNRAS.108.252B

⁴⁰ “A New Model for the Expanding Universe,” MNRAS 108 (1948) 372, adsabs.harvard.edu/cgi-bin/nph-bib_query?bibcode=1948MNRAS.108.372H

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