GRAVITATIONAL COLLAPSE, COSMIC BLACK-BODY RADIATION, AND THE ORIGIN OF ASTRONOMICAL SYSTEMS

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ABSTRACT

The current interpretation of the cosmic microwave background as the remnant of an unexplained primeval fireball would make it impossible to construct a self-contained theory for the origin of galaxies and other astronomical systems. The alternative interpretation presented here accounts for both the quality and the quantity of the observed radiation, and provides a framework for a self-contained cosmogony. The microwave background is identified with the thermal output of certain cataclysmic processes whose nonthermal manifestations include quasars and cosmic rays.

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Modern science is rooted in the conviction that an understanding of the structure, evolution, and origin of the physical universe does not require sweeping *ad hoc* assumptions of the kind that characterized pre-scientific cosmologies. Ironically, this conviction is now threatened by inferences deriving from the most significant advance in observational cosmology since Hubble's announcement of the cosmic expansion in 1929: the discovery by Penzias and Wilson of an isotropic and all-pervading field of "black" (i.e., thermal) electromagnetic radiation at a temperature of 2.7° K. I shall first describe these inferences and then offer an alternative theoretical interpretation of the Penzias-Wilson radiation.

In an expanding universe the momentum of any free particle varies inversely as the cosmic scale factor $a(t)$, defined as the distance between two fixed but arbitrary elements of the uniform and uniformly expanding cosmic substratum. This rule, which applies to photons as well as to material particles, implies that both the temperature and the specific energy (energy per unit rest mass) of a thermal radiation field vary inversely as $a(t)$.

Thus as we look backward in time we see higher and higher temperatures and larger and larger ratios between the energy of the radiation field and that of the matter. At present, ten billion years after the beginning of the cosmic expansion, the energy of the radiation field is one one-hundredth of one per cent that of the matter; ten thousand years after the beginning of the cosmic expansion, the energy densities of radiation and matter would have been equal and the temperature of the radiation would have been ten thousand times greater than its present value; and in the earliest stages of the expansion, radiation, at enormously high temperatures, would have dominated completely. According to this picture (originally put forward by Gamow in 1948 and recently revived by Dicke and his colleagues at Princeton) the universe began as an infinitely hot, infinitely dense fireball containing infinitesimal traces of matter.

The arresting and poetic quality of the fireball hypothesis has tended to obscure the prosaic fact that it does not actually explain very much. It does not explain why the temperature of the black-body radiation is 2.7° K instead of .0027° K or 270° K -- or even why the radiation is there at all. But there is an even more serious difficulty with the fireball hypothesis. The central problem in cosmogony is to understand the origin of structure in the universe. One assumes, of course, that there has been a real growth of complexity, not merely a transformation of one kind of complexity into another; otherwise the cosmogonic problem would be meaningless. But this fundamental assumption flatly contradicts the fireball hypothesis, for it has been demonstrated that significant density fluctuations would never develop in an initially structureless, radiation-dominated universe. Instead of convening into the complex hierarchy of self-gravitating systems revealed by astronomical observations, matter would remain more or less evenly distributed throughout space. If, then, we accept the fireball hypothesis, we must postulate that considerable unexplained and unexplainable structure was present in the initial state of the universe. But the situation may be even worse. Certain theoretical and observational considerations suggest, though they do not yet prove, that *whatever* assumptions one makes about initial structure, the fireball hypothesis is inconsistent with existing astronomical observations.

The alternative to the hypothesis of a primordial fireball is the hypothesis that the universe began to expand from its lowest possible energy state, at absolute temperature zero. My students and I have studied the early evolution of an initially structureless "cold" universe, and have found indications that at a certain stage in its expansion it becomes unstable against the condensation of galaxy-sized masses in much the same way that an expanding vapor becomes unstable against the formation of liquid droplets. Although this conclusion is not yet firmly established, let us suppose, for the sake of the argument, that it is correct. The question then arises, whether the Penzias-Wilson radiation can be produced by physical processes occurring in a cold universe.

Attempts to account for the radiation in this way encounter two main difficulties. (1) The specific energy of the radiation greatly exceeds that of all other known forms of energy, with the single exception of rest-mass energy. Thus exceedingly powerful sources of an unfamiliar kind must be invoked. These sources would have produced a dilute field of high-temperature radiation. (2) The fact that the radiation is now black implies that it has been thermalized by interactions with matter. This in turn implies not only that the universe was highly opaque when the radiation was emitted but also that the matter responsible for the opacity could radiate efficiently in a specific, rather narrow wavelength range. These requirements are clearly very restrictive. Nevertheless, I shall argue that there exist independent theoretical and observational arguments from which it can be inferred, without benefit of *ad hoc* assumptions, that a cosmic radiation field having approximately the observed characteristics ought to exist. Of course, these arguments would have been more convincing had they preceded the observation of Penzias and Wilson, but in science as in other human activities foresight is rarer than hindsight.

The most powerful of all known energy sources are radiogalaxies and quasars (probably immature radiogalaxies rather than a distinct astronomical species). The nonthermal radiation of these objects is emitted by ultrarelativistic electrons spiraling in ordered magnetic fields. The magnetic fields and ultrarelativistic electrons present in a typical quasar are thought to contain more energy than would be liberated by the annhilation of a million solar masses. What is the source of this energy? The most efficient, and in my opinion the most plausible, of the proposed sources is the gravitational collapse of a supermassive gas cloud ($M = 10^{10} - 10^{12} M_{\odot}$) to a radius somewhat greater than the Schwarzschild limiting radius $2GM/c^2$. The specific energy that could be released in this way is comparable to the theoretical upper limit $c^2 = 10^{21}$ erg/gm. I have discussed elsewhere how certain technical difficulties connected with this idea (notably the premature onset of instability and the classical angular momentum difficulty) can be overcome, and have shown how a significant fraction of the energy liberated is converted first into magnetic energy and then into the kinetic energy of ultrarelativistic charged particles, including cosmic rays and ultrarelativistic electrons trapped in nonthermal radio sources. Now, it is a matter of practical experience that the manufacture of high-energy particles is inherently wasteful and inefficient.

Philip Morrison has remarked, in another context, that when one flies over the giant particle accelerator at CERN, Geneva, one sees no sign of the intricate apparatus used to generate the enormous magnetic fields and ultra-relativistic particles: it is completely hidden by huge clouds of steam, for only a tiny fraction of the power generated at CERN actually appears in nonthermal form; the rest appears as heat. I suggest that the Penzias-Wilson radiation is related to the nonthermal radiation from quasars and radiogalaxies much as the steam over CERN is related to the magnetic fields and high-energy particles of which it is a by-product.

Can this hypothesis account for both the quantity and the quality of the radiation? Consider first the question of quality. The statistics of extragalactic radio sources indicate that as we go backward in time the rate of formation of these objects at first increases and then abruptly cuts off. The most natural explanation is that quasars began to form at the same time as the galaxies, between three and six hundred million years after the beginning of the expansion. Because the newly formed galaxies were nearly in contact with one another and because solid grains comparable in their properties to those that now exist in interstellar space would then have been present in appreciable numbers -- theoretical calculations show that such grains require only one hundred million years to form -- the universe must have been highly opaque to light of visible and shorter wavelengths. The grains, which are thought to be made up of various ices and graphite, are not only efficient absorbers of high-temperature radiation but are also efficient emitters of thermal radiation at temperatures of a few tens of degrees. Thus they have precisely the properties required to thermalize the high-temperature radiation that would be emitted by collapsing supermassive gas clouds.

As to the quantity of the emitted radiation, perhaps the most direct estimate comes from considerations of the efficiency of quasars and radiogalaxies as particle accelerators. If we knew the high-energy output and the efficiency of the CERN accelerator, we could immediately calculate its thermal output. The theory of nonthermal radio sources cited earlier predicts that a large part of the nonthermal energy liberated by a supermassive gas cloud ultimately goes into extragalactic cosmic rays. Thus if we could measure the energy of the part of the cosmic-ray flux that is produced by extragalactic sources, we would have a quantity exactly analogous to the energy of ultrarelativistic particles manufactured by the CERN accelerator. Fortunately, it does turn out to be possible, by utilizing measurements at the very highest observed energies, to separate the extragalactic contribution to the cosmic-ray flux from the much larger galactic contribution;

and the energy of the extragalactic contribution turns out to be about one per cent that of the Penzias-Wilson radiation field! This is about what we should have expected on the basis of our present hypothesis. Man-made particle accelerators have efficiencies considerably smaller than one per cent, but for technical reasons (gravitational containment, high electrical conductivity of rarified plasmas) naturally occurring particle accelerators may be expected to be considerably more efficient.

Thus the two most exciting astronomical discoveries of recent years, quasars and the cosmic microwave background, may well prove to be aspects of a single physical phenomenon: the gravitational collapse of supermassive gas clouds that condensed in an initially cold universe.

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