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The twentieth century has seen many remarkable advances in both physics and astronomy which have radically altered our conceptions of the universe around us. We now know that on the largest scale we can observe, the galaxies are receeding from each other and from our own galaxy, many of them at speeds close to the speed of light. If we extrapolate this recession back about 13 billion years into the past, we find that all of the galaxies would have been merged and the universe then would have consisted of a rather dense blob of small dimensions, perhaps even approaching a singular point. For the past 13 billion years then, the universe has been expanding outward from that point like an enormous balloon. This picture of the universe, developed by Friedmann, Lemaitre, Hubble and Gamow, is known as the "big-bang" cosmology.

Within the past decade, Arno Penzias and Robert Wilson of Bell Telephone Laboratories accidently discovered a background of cosmic microwave radiation appearing to come from all directions in the sky with equal intensity. This radiation turned out to have the same intensity and frequency distribution characteristic of an ideal type of thermal radiation known as "blackbody" radiation. This is the name given to radiation from a perfectly absorbing (i.e. black) and emitting object which could not be explained by classical physics and whose ultimate explanation led Max Planck to his classic paper formulating the beginnings of the quantum theory. Blackbody radiation would also be expected to fill an oven with perfectly reflecting walls containing an object radiating in thermal equilibrium with its surroundings. In other words, the universe is in a sense, a vast "microwave oven" from which no radiation can emerge. This oven is now at a temperature of approximately 3° K (i.e. 3°C above absolute zero). This is indeed a very cold temperature now, but if, as it appears judging from the extremely isotropic nature of this radiation, the whole universe is at this same temperature, this indicates that at some time in the past the universe must have been at a dense enough state to reach thermal equilibrium as indicated by the blackbody frequency distribution of the radiation. For thermal equilibrium to be attained, the universe would have once had to have been at least a billion times more dense than it is at present and had to have been hot enough so that all of the matter in the universe was in the form of an ionized gas, or plasma. This fact is what has convinced almost all astronomers of the big-bang cosmology(as opposed to the steady state cosmology which says that the universe was always at the same temperature and density as it is now).

The microwave blackbody radiation, as with all electromagnetic radiation, can be thought of as consisting of individual photons. These photons,at present, fill the universe to a density of some 400 photons per cubic centimeter, and this is true for every cubic centimeter in the vast reaches of intergalactic space. This means that there are between 100 million and 10 billion photons for every atom that exists in the universe. How did these photons originate?

The question of the origin of the cosmic photons is intimately connected with other twentieth century discoveries; those in the field of particle physics. In 1928, Paul Dirac, using the principles of the then new quantum mechanics combined with those of Einstein's theory of relativity, derived an equation to describe the behavior of the electron. The Dirac equation, which is a direct consequence of applying relativity theory to quantum theory, led to the prediction of a positively charged electron, or "positron", which would have the same mass

m_e as an electron. Furthermore, should this positron collide with an ordinary, negatively charged, electron, they would both vanish and their masses would be converted into pure electromagnetic energy in the form of gamma-rays. In accordance with the theory of relativity, a positron and electron coming together with very little kinetic energy would annihilate into two gamma-rays, each with an energy $m_e c^2$. Conversely, two gamma-rays, each with energy $m_e c^2$, could collide to produce a pair of oppositely charged electrons of rest mass m_e. This process is referred to as "pair-production" and is a commonly observed phenomenon in particle and cosmic-ray physics. Positrons were discovered in the cosmic-radiation by Anderson in 1932.

The proton too has its oppositely charged counterpart called the antiproton. The neutron has an "anti" counterpart which has opposite magnetic properties. The particles also are created in pairs with their anti-partners and are mutually annihilated in pairs. Indeed, every subatomic particle has a corresponding antiparticle. Recently, a Russian group at Serpukhov reported the discovery of an antitritium nucleus, further proof of the physical reality of antimatter.

Let us picture an atomic system consisting of a positron and an antiproton. Such an atom would be antihydrogen. A gas made up of antihydrogen would radiate the same way as a gas of hydrogen; we would observe the same well-known series of Balmer spectral lines. Indeed, a distant galaxy made entirely of antimatter would look just like an ordinary galaxy when observed through a telescope or through a telescope spectrograph. There would be no way to tell them apart. We could well ask ourselves then if some of the distant galaxies we see with our telescopes could be made of antimatter.

We may go further and speculate that half of the distant galaxies should be antimatter, since it has been established that particles and antiparticles are always created in pairs. To a theoretical particle physicist, there appears to be a profound symmetry in nature between particles and antiparticles which should hold on a universal scale if the laws of physics are the same everywhere in the universe.

Of course, if matter and antimatter are to exist together in the same universe, they must exist in separate places or they would annihilate each other in a burst of radiant energy. How could this separation be accomplished in the big-bang cosmology?

An answer to this question has been suggested by Roland Omnes of the Laboratory for Theoretical and HighEnergy Physics at Orsay,France. Omnes starts out by examining the physics of particles and antiparticles in thermal equilibrium in the primeval "fireball" stage of the big-bang when the universe could have been at a temperature of about three trillion degrees. At this stage, the density of the universe was so high that all of the particles and antiparticles were squeezed together. Arguing from evidence obtained recently with particle accelerators, Omnes suggested that nucleons and antinucleons at this density would act as if they repel each other over nuclear distances.

If we imagine a box filled with equal amounts of red balls and black balls later to be symbolically identified with nucleons and antinucleons, we further specify that the red balls and black balls repel each other, i.e., unlike species repel, like species have no effect on each other*. If we then start out with a well mixed assortment, bouncing along in the box with some low kinetic energy compared with the energy of repulsion, and then we wait long enough, we will find that these balls will eventually segregate themselves into clumps of red balls and clumps of black balls. This is basically how Omnes' separation mechanism works; it leads to a universe of separate domains of matter and antimatter. Of course, our balls-in-the-box picture is greatly oversimplified since we have not allowed for the facts that (1) the "box" being the universe, is expanding and (2) our red balls and black balls can annihilate and be recreated in pairs in thermal equilibrium

*This is, of course, a strong interaction we are talking about.

at the ambient temperature of the universe. But, nevertheless, the result, according to Omnes' calculations and those of Evry Schatzman of the Paris Observatory, is the same - large scale separation of matter and antimatter. The separation is a phase transition effect, similar to that observed in a gas of magnetic molecules being lowered to a critical temperature. In the case of a magnetic gas, the magnetic moments of the molecules align themselves in regions of dimensions much larger than the scale of the individual molecular magnetic forces. The creation of ferromagnetic domains in a bar magnet is another example of a critical phase transition phenomenon which has been studied both experimentally and theoretically. A mathematical model of a two-component system where like species do not interact and unlike species repel has been discussed by Widom and Rowlinson of Imperial College, England and by David Ruelle of Yeshiva University, New York.

In Omnes' theory of the early stages of the big-bang, as the matter and antimatter domains in the universe coalesced and expanded, annihilation still took place on their mutual boundaries. In fact, so much annihilation took place that roughly only one proton (or antiproton) in a billion survived to the present time. What happened to all the energy released by the annihilating particles? It became the very same blackbody radiation that Penzias and Wilson discovered!

Thus, the following picture emerges. Originally, the universe was in a dense, ultrahot, fireball state of pure radiation. The radiation was in the form of gamma-rays of high enough energy to produce electrons and positrons, protons and antiprotons, neutrons and antineutrons, and various other particles, in matter-antimatter pairs. Eventually, the universe expanded and cooled to the point where there was not enough energy in the thermal radiation to produce pairs of nucleons and antinucleons. All this cooling occured within a fraction of a second. But at this stage, the universe was still dense enough so that Omnes' repulsive separation mechanism could start to drive matter and antimatter into clumps. Still, almost all of the matter and antimatter was destroyed and ended up in the form of the microwave blackbody radiation. But enough of the matter and antimatter survived, because of the separation mechanism, to eventually produce the stars and galaxies, planets and life that we knows exists in the universe today.

The Omnes picture leaves off when the universe had cooled to about 30,000°K, about 100,000 years after the "big-bang" started. At this time, the raidation energy density and matter energy density in the universe were about equal and the matter and antimatter domains had reached a size large enough to encompass about as much mass as an average galaxy. This is the point where I, together with Jean-Loup Puget of the Paris Observatory, started examining the further evolution of the Omnes cosmological model. We first realized that annihilation taking place on the boundaries of these regions would set up strong pressures from high-energy electrons and positrons and gamma-rays produced by the annihilation of protons and antiprotons and X-rays produced by the electrons and positrons. This radiation pressure would fluctuate from one place to another but would, in general, be in the direction away from the boundary regions where the annihilation was taking place. Conditions would then be excellent for generation of turbulent motions in the matter and antimatter regions which were then in the plasma state. The annihilation would also help cause the further coalescence of matter and antimatter domains into regions comparable in mass to clusters of galaxies. Out of these regions, in our picture, clusters of galaxies eventually formed, with the galaxies contracting out of the swirling turbulent eddies of gas caused by the annihilation pressure.

When the universe had expanded and cooled to a temperature of about 3,000 °C (or slightly lower, according to our picture) the protons and electrons began to form hydrogen atoms and the antiprotons and positrons started to combine into antihydrogen atoms. When this change of state occurred, two very important changes were caused in the physics of the turbulent fluid motions produced by the annihilation pressure. First, these motions became supersonic. This happened not because of any increase in the speed of the fluid motions; rather it occurred because the speed of sound in the fluid dropped precipitously. The speed of sound is the speed at which an impulse can be transmitted by a pressure wave in a fluid. When the cosmic gas was in its ionized plasma state, it consisted of electrically charged particles which could easily transmit momentum to the numerous electromagnetic blackbody photons left over from the primeval fireball. The photons would then transmit the momentum of any pressure waves in the plasma very efficiently at almost the speed of light. Any fluid motions caused by annihilation had velocities considerably less than the speed of light and were therefore subsonic. Pressure changes caused by these motions could not build up into permanent density fluctuations because such fluctuations would be radiated away at almost the speed of light, faster than they could be built up. Thus, the plasma acted like an incompressible fluid. However, when the plasma combined to form an atomic gas as the temperature dropped low enough for this to happen, the speed of sound dropped roughly to the thermal speed of the atoms of the gas which then had to transmit momentum on their own, no longer being electromagnetically coupled to the blackbody radiation. As a result, the speed of sound dropped roughly to 0.0001 of its original (plasma) value and the turbulent motions became supersonic. This led to the buildup of density fluctuations large enough so that they could eventually start to contract gravitationally to form galaxies. Our picture here is similar to earlier suggestions of Carl von Weiszäcker and George Gamow that turbulence could lead to galaxy formation. At present there is a large and active group of cosmologists around the world working on the turbulence theory of galaxy formation. However, we feel our extension of the matter-antimatter domain model fills a gap in the theory; it provides a continuous source of the energy needed for generating the turbulence, namely annihilation pressure, and we have been able to make estimates of the turbulent velocities induced in the cosmic gas based on the calculated rate of matter-antimatter annihilation indicated by our model.

The second important change in the physics of the cosmic gas motions which occurred when the plasma combined into an atomic gas was that the fluid viscosity dropped to 10^{-8} of its original (plasma) value. This is because when the gas was in a plasma state, it interacted electromagnetically with the vast number of blackbody photons in the universe, efficiently transmitting momentum. Again, when the plasma combined into a gas of electrically neutral atoms, it "decoupled" from the blackbody radiation, resulting in a dramatic drop in the fluid viscosity. This drop in viscosity allowed turbulence to exist in the atomic gas over a wide range of eddy sizes without being rapidly dissipated. The large changes in the sound velocity and viscosity are thus related phenomena, both due to the fact that when the cosmic fluid changed from a plasma state to a gaseous state it decoupled from the blackbody radiation.

We have made estimates of the mean density and rotational velocity of galaxies formed in our model and have found values in good agreement with those obtained by observations of galaxies. Our turbulence picture leaves galaxies spinning with a mean rotational velocity of the order of hundreds of kilometers per second.

Matter-antimatter big-bang cosmology thus leads to some encouraging concepts of the universe. It is philosophically pleasing to find that a basic symmetry which occurs on the subatomic level may also hold on the cosmic scale. It may account for why there are about a billion photons for every atom in the universe. It may be able to also explain some recent observations of an unexpected flux of cosmic gamma-rays which may be our most direct evidence of the existence of antimatter in the universe, a point which I will now discuss.

The final test of any theory must lie in observation and we must eventually look for some clue that large amounts of antimatter may exist in the universe. The most direct way, of course, is to try to find cosmic antimatter, and the logical place to look for it is in the cosmic radiation. As of this writing, there is no firm evidence for primary antimatter in cosmic rays and it appears that they can make up no more than about one part in a thousand (at most) of the cosmic rays reaching the earth. Unfortuately, the observational problem appears to be far too subtle to be solved in such a direct manner. Such direct tests are not good tests of our picture because in our model, antimatter cosmic rays could only come from distant clusters of galaxies and there is little likelihood of their reaching us if they have "moderate" energies (i.e., about 1 to 10 billion electron volts) in the range where antimatter searches have been performed. Indeed, most astrophysicists believe that all but perhaps one part in ten thousand of the 1 to 10 billion electron volt cosmic rays come from sources in our own galaxy and even if half of the remaining "extragalactic" cosmic rays are antimatter, we should not be able to distinguish them from antimatter cosmic rays produced in pairs in high energy cosmic-ray collisions in our own galaxy. At the very highest observed energies (10^{17} to 10^{20} electron volts) extragalactic cosmic rays could contribute more to the total amount since such cosmic rays cannot be contained long by the galactic magnetic field. Here again, however, we reach an impasse. These cosmic rays are detected by the large showers of secondary particles produced by them in the atmoshere and there is, unfortuately, no way of determining the charge of the original (primary) cosmic ray by studying the vast numbers of secondaries in these showers.

How else then can we look for evidence of cosmic antimatter? The next best way is to look for the products of the annihilation of protons and antiprotons which should interact on the boundaries between matter and antimatter domains in the universe. Of these products, the electrically neutral gamma-rays and neutrinos are unaffected by galactic and extragalactic magnetic fields and can reach us from the extremely large distances between the clusters of galaxies. The neutrinos, however, are very difficult to detect and there is not much point in looking for them with our present technological capabilities. The gamma-rays offer the best hope. In particular, it is most promising to look for the gamma-rays which were produced in the past when the universe was in a denser state and the matter-antimatter annihilation rate was correspondingly higher. These gamma-rays were originally produced in the decay of neutral pi-mesons which were the products of proton-antiproton annihilations and had an energy of about 100 million electron volts (MeV) with a characteristic peak in their energy distribution at about 70 MeV. However, due to the expansion of the universe they have been "redshifted". Their frequency has decreased due to the Doppler effect because their points of origin are moving away from us. The decrease cf frquency has long been observed in the spectral lines of distant galaxies in the optical region of the electromagnetic spectrum where the lines were seen to be shifted toward the red end of the spectrum, thus the name "redshift". Because, according to the quantum theory, the energy of a photon is proportional to its frequency, redshifted gamma-rays from distances of over 10 billion light years have energies typically below 100 MeV. However, almost all gamma-rays which we would expect to observe below an energy of about 1 MeV are expected to be attenuated by collisions with cosmic electrons. Thus we expect that cosmological matter-antimatter annihilation will produce a characteristic spectrum of gamma-rays coming from all directions isotropically and being most observable at energies between 1 and 100 MeV.Two years ago, I published a paper in Physical Review Letters with David Morgan and Joseph Bredekamp, giving the results of our predictions of the form of the expected annihilation gamma-ray spectrum and comparing them with the little observational data available at that time, which extended up to 6 MeV and gave some preliminary indications in accord with our predictions. This year, however, more recent measurements have been made of the cosmic gamma-ray background spectrum which extended the spectral information up to an energy of 30 MeV using gamma-ray detectors placed aboard Apollo 15 and 16. These measurements were made by a team headed by Jacob Trombka of Goddard Space Flight Center, Albert Metzger of the Jet Propulsion Laboratory and James Arnold and Lawrence Peterson of the University of California. Measurements of the cosmic gamma-ray background spectrum were extended to 135 MeV recently using a spark chamber telescope flown aboard the second Small Astronomy Satellite by a group headed by Carl Fichtel of the Goddard Space Flight Center. The Apollo and Small Astronomy Satellite data have delineated a smooth continuous cosmic gamma-ray spectrum extending up to about 135 MeV which shows the spectral features which we predicted in our calculations published two years ago. Within the experimental error of the data (about 30 to 50%) the new measurements show the characteristics of a spectral component of redshifted gamma-radiation from cosmological matter-antimatter annihilation which are (1) a flattening of the gamma-ray spectrum in the vicinity of 1 MeV, (2) an increased gamma-ray flux between 1 and 100 MeV being approximately a factor of ten greater than the expected flux at 20 MeV, and (3) a very steep spectrum between 50 and 135 MeV. The data fits well with our theoretical predictions over two decades in energy and five decades in intensity. This evidence is, to us, most encouraging and very exciting. However, it is still new and must be verified by future observations and future theoretical calculations.

The study of nuclear physics led us to an understanding of the stars, their energy generation and life history. It now appears that our more recent knowledge of particle physics may be leading us to a deeper understanding of the large-scale structure of the universe in which we live.