

THE PRINCETON GALAXY

Four Princeton scientists fire a starburst of ideas about ends, beginnings, transformations and reincarnations: "cycle after cycle, not only of man but of the universe itself"



Robert H. Dicke:
Big-bang radiation



Jeremiah P. Ostriker:
Deaths of stars



Remo J. Ruffini:
Evidence
of black holes



John A. Wheeler:
The moment
of collapse

Interviews by Florence Helitzer

The language of modern physics is alluring. Such words as "birth," "death" and "rebirth" and phrases like "cycles of creation and destruction" constantly recur. These words have been encountered before in other contexts: in myth and fairy tale, in oriental religion and in the Bible, in literature and in philosophy. The past overflows with them.

In an attempt to find a bridge between past culture and current physics, now reaching into an immense universe, questions drawn from religion, mysticism and philosophy were put to four eminent cosmologists who teach and do research at Princeton University. Since modern physics was our point of departure, it became necessary during the course of the interviews to elucidate some of its concepts.

The four scientists, who were interviewed separately, are:

Dr. Robert H. Dicke, Cyrus Fogg Brackett Professor of Physics. In 1965

Dr. Dicke and his research group revived the hypothesis of Gamow and Alpher that the universe was born in the explosion of a primordial fireball. Dr. Dicke suggested that radiation from this "big bang" should be detectable as radio waves in space. At about the same time, a Bell Telephone Laboratories team detected such radiation but couldn't explain it until learning of the Dicke theory. Another of Dr. Dicke's interests is gravitation physics. He suggests the existence of a "scalar" gravitational field to account for part of the gravitational attraction, thus questioning Einstein's general theory of relativity.

Dr. Jeremiah P. Ostriker, Professor of Astrophysical Sciences. Dr. Ostriker's theme could be described as the deaths of stars. Last year he won the American Astronomical Society's Warner Prize for his contributions to the theory of rotating stars, in particular for investigations of the internal structures of rotat-

ing white-dwarf stars and for a theory of pulsars.

Dr. Remo J. Ruffini, Assistant Professor of Physics. Dr. Ruffini, who works in close collaboration with Dr. John A. Wheeler, recently reported having found persuasive evidence for the existence of black holes in space, bizarre dense objects that may be the remains of stars that have undergone gravitational collapse. The gravitational field of a black hole is so strong that nothing can ever escape from it. Such an object is invisible because it emits nothing—not even a light ray.

Dr. John A. Wheeler, Joseph Henry Professor of Physics. Dr. Wheeler, one of the first American scientists to concentrate on nuclear fission, worked with Niels Bohr in 1934 and again at Princeton in 1939. His research has ranged from elementary particles to gravitation and the cosmos. Dr. Wheeler has worked out a detailed description of the black hole, including what happens at the

moment of collapse. He views the black hole as an omen for the future gravitational collapse or death of the universe [see ID, December 1972].

Each scientist consented to the interview for similar reasons. For example:

Ostriker: There are a lot of similarities between the mystic's view of the world and Einstein's [see "The Quotation Game: How Can You Tell a Physicist from a Mystic?" ID, February 1972]. I don't know whether it's coincidental that currently the best cosmology is a "big bang" cosmology and that the best potential rival is a cyclic one, which is more like the Eastern view. I am intrigued. I suspect that I could learn a lot just from thinking and talking about it.

Wheeler: Through the very process of talking about such issues, one tends to understand them better. It's like the little old lady who said, "How do I know what I think until I hear what I say." But then there is the other side of it—that one has to be very humble in the face of people who have dealt with these eternal issues over so many generations.

We began by trying to focus on the nature of the observer rather than on what is observed. Specifically, we tried to pinpoint a mysterious and elusive human process: intuition. There was an assumption that past religious cosmologies had evolved intuitively. There was also a corollary that the mystic's view of the cosmos is largely intuitive and often ineffable . . .

Q

Is it possible to have knowledge without adequate language or the precise and defined way of communicating that science offers?

Ostriker: I don't think people know what produces ideas. They may know where they start and where they finish. The mystics' experiences might be analyzable if we knew enough about the series of steps. You may know that if you fill your tank with gasoline and then press the accelerator, the car will go. You might not know what goes on inside, but you can predict the result. There are many things we can't see. You think about a problem, and you wake up in the morning with a solution to it. It's possible that it was some divine leak. We simply can't say.

Q: What has been your experience

with intuition?

Ruffini: You seem to hit something that is true in nature. You study and work for a long time, and once in a while you feel that something is true. You cannot justify it at the moment, because the experiment to test and verify your theory has not yet been performed. Still, you have this feeling that your intuition is really in correspondence with nature. To keep knowledge moving, we need a lot of work and a great many challenges. And nothing is more challenging than this feeling of finding something new.

Q: Is there any way of analyzing human intuition?

Dicke: Intuition is very interesting. It plays a powerful role in the origin of theory, and I don't think we know very well what it is except that an element of trial seems to be very important.

Q: Can we try to define it a little bit better? From your previous description, a prerequisite would be education or experience with the problem.

Dicke: That's right. I think you must have some background knowledge, or else an intuitive solution, an intuitive seizing on an idea, would be ridiculous.

Q: Can intuition be prophetic? Can it tell you things you have no real way of knowing from experience?

Dicke: I would think intuition comes out of past experience. In a sense you knew but perhaps didn't realize that you knew.

Q: Why do so few people seem to have intuition?

Dicke: That is both true and interesting. Intuition has an aspect of creativity too, doesn't it? For example, there could be an extremely capable mathematician who knew almost everything that's ever been discovered about mathematics and could reproduce it. But he might not be able to create new mathematics. This kind of encyclopedic knowledge is without creativity. Yet someone whose knowledge is not so widespread may be more creative. I think a strong element in intuition and creativity involves quickly examining a number of possibilities and throwing out the obviously ridiculous ones.

Q: Does anything else happen?

Dicke: I suspect that images play an important role in creative thinking. Even when I'm dealing with a very abstract idea, such as the multidimensional space in which one pictures the state of an atom, I have a rough mental image of that space. It's strange that we can form

an image of such an abstraction as space.

Q: Will you then proceed from image to analogy?

Dicke: Yes, modeling. The theoretical structure of physics is a mathematical model. That's what is so beautiful about it. There isn't quite a one-to-one relationship, but theory provides a reasonable model of the world that can be manipulated in mathematical symbols. The process of carrying out a theoretical investigation is something like an experiment. And that's a really lovely concept—an experiment carried out without apparatus. The theoretical experiment is performed sitting in your armchair: you decide from the theoretical structure what would happen if a real experiment were performed. Then you actually perform the experiment to see whether or not it behaves the way the



For ID in Princeton and New York City, photographed by Susan Lombardo

"Intuition comes out of past experience. In a sense you knew but perhaps didn't realize that you knew." — Dicke

conceptual one did.

Q: Does the intuitive process, then, rely more on modeling or symbolism than it does on language?

Ostriker: Very often there is a discovery in physics, and then someone else rediscovers the same thing using different language. Only after considerable work do they realize that they have

both discovered the same thing. So, in a sense, the fact was there and the language disguised it. The means of discovery may involve a symbolism that is not linguistic. For example, Einstein thought geometrically. Most physicists seem to think in mechanical images, perhaps because of their education in Newtonian physics. So they learn to make models in their heads. Or they think in geometrical images because of their background in mathematics.

This is a world of pure mathematics, and when we penetrate to the bottom of it, that's all it will be"—Wheeler



Mathematics and the Physical World

Q: Mathematics has often been compared to a chess game, which, though valid and often exciting, doesn't tell us anything about what might be happening even one inch away from the chessboard. So why and how does mathematics work for the physical world?

Dicke: There's a structure to mathematics that has no obvious inherent relation to the structure of the physical world. But, interestingly enough, several branches of mathematics have developed that have been useful in describing the physical world. It's not clear that there should be any connection at all. It's true that when you look at the structure of mathematics you find a

game, like chess, played with rules, a formal structure. Yet, you reason and think about the external world in relation to the mathematical structure of physical theory. Like moves on the chessboard, you play with the formal mathematical structure of the physical theory and gain some understanding of the physical world itself, with no direct observation. (Of course, the theory originated in a host of observational results.) Later you make an observation to see whether you're off the track or not. This observation is the essential part—without this there can be no science.

Ruffini: How a mathematical structure can correspond to nature is a mystery. One way out is just to say that the language in which nature speaks is the language of mathematics. This begs the question. Often we are both shocked and surprised by the correspondence between mathematics and nature, especially when the experiment confirms that our mathematical model describes nature perfectly.

This surprise and shock automatically pose a different question, which some people choose to answer in a religious manner and others refuse even to ask. At this point the decision involves recognizing the presence of a god who has arranged it all. To some people the question does not make sense. Still, common to both these attitudes is the feeling of surprise and happiness in discovery, which generates a deeper respect for nature. Nature appears to us simpler and more and more beautiful. This serenity and happiness is, I think, exactly the feeling that in the past was called the religious feeling.

Wheeler: As one looks around at the trees and flowers and birds, this wealth seems to be about as far as possible from anything mathematical. It's only when we look into nature in more detail that we realize that it's made out of these cells and those genes and these molecules and those atoms and these particles. And the simplicity is there—it's inescapable! But what makes us think that as we go on we're going to come closer to the world of mathematics? I suppose that there's nothing more comforting than that this is the way it has been. Eugene Wigner [Nobel Laureate in physics and a colleague] puts it in a marvelous phrase of his, "the unreasonable power of pure mathematics."

The fact is, it works and we tend to use what works. But why should mathematics work? Other people have put it

in language far more vivid than I can hope to do—the idea that this is a world of pure mathematics and when we penetrate to the bottom of it, that's all it will be. We don't have to go to the people in the world of logic and mathematics to hear that all existence is a dream and we are the stage managers of this dream. But it's healthy and helpful, in this connection, to refer back to [the seventeenth-century philosopher and mathematician, Gottfried von] Leibniz because he says, whether it's a dream or not, it's a world in which reason offers a way to make progress and helps us along every step of the way.

Faith in the Power of Science

Q: There are two imponderables here: the dream and the "unreasonable power of mathematics." I don't see how scientists, aware of these dilemmas, can have such faith in their observations, reasonings, mathematical constructs, theories.

Ruffini: I can only answer with an example. After pulsars [stars that have undergone partial gravitational collapse and are emitting light in sharply defined pulses—also called neutron stars] were discovered, I spoke with Emilio Segrè, who was awarded the Nobel Prize for his discovery of the antiproton. I told him we were finally convinced that we had found neutron stars. And Segrè, speaking in elegant, old-fashioned Italian, said, "Perhaps God is so powerful that He could find a different way of making a pulsar than with a neutron star. How can you be so definite in saying you have found a neutron star?" He was alluding, I think, to the problem of the theoretician, which is not just to find a correspondence between his theoretical framework and the physical world but to find the *unique* correspondence.

Q: How can you be so definite?

Ruffini: Physics is an expanding frontier. As more data are accumulated, new theories and predictions arise to fit the data; but these in turn demand more experiments and observations. There is a constant feedback between experiment or observation and theory, with the experiments either confirming the theory or altering it.

In the case of the black holes, which emit neither radiation nor light, evidence for their existence has to be indirect. The reasoning was that if a black hole exists as part of a binary star system, it will be detectable through its influence on its luminous companion. In

sucking material from the normal living star, the black hole will overheat the falling material. The overheated material will emit an enormous amount of X rays, equal to some 10,000 times the luminous energy of our own sun.

Q: And you found such X-ray sources?

Ruffini: Yes. The American Uhuru satellite has recently discovered such X-ray sources. Their features are so unusual that we see no other way to explain them except through neutron stars and black holes.

The data on these X-ray binary stars, collected every day from the Uhuru satellite and from radio and optical telescopes around the world, fit our theoretical predictions marvelously well. Nevertheless, we consider most seriously any alternative explanation. Much of the excitement comes from proving or disproving, on the basis of the experimental results, alternative explanations of the same phenomena. In this light there has been much speculation recently on the uniqueness of the final configuration of gravitational collapse. Our group has been examining how many different kinds of black holes we could have and devising experimental checks to pin down the differences among them.

Some scientists have even speculated on the possible existence in nature of "naked singularities"—what we could perhaps call black holes without horizons: regions of space in which the density of the material becomes so high and extreme that the entire formalism of theoretical physics, as known today, will break down, and totally new phenomena could occur. Though fascinating and extremely challenging from a theoretical point of view, these "naked singularities" do not seem to me to be very realistic. No experimental evidence exists today of any major breakdown in our theoretical framework.

Q: Why do you have so much faith in science—especially in cosmology, where so little is actually observed?

Dicke: Surprisingly, the amount of information is increasing rapidly. Astronomical observations show an expanding universe, and from the rate of expansion, we can project back to a beginning. These conclusions are indirect, based on observations of stars, galaxies, microwaves and radioisotopes. And there is an involved analysis of stellar evolution that permits us to decide how old some of the oldest stars in our galaxy

are. This age is found to be the same as that for the expansion of the universe as a whole, so we believe that these stars must have formed near the beginning of the expansion.

Q: I am puzzled about the relationship between theory and experiment. Which represents the act of faith?

Ruffini: As far back as 1630, Galileo introduced the dogma that the final judge for scientific theory is the experiment. The experiment is our way of posing the right question to nature. The answer or solution that emerges from it is assumed to be unchanging in time and space. If performed under the same conditions, the experiment will always produce identical results. Our faith in the reproducibility of the experiment is indeed a dogma. And dogmas can appear to some to be unreasonable and rigid. But the most compelling reason for our faith is the extraordinary amount of knowledge we have acquired in natural science through our acquiescence to Galileo's dogma.

Q: Will the next step be toward more and more complex observational instruments and experimental apparatus?

Wheeler: I suspect that the next step will be determined more by pure thought than by experiment. The worst possible thing would be to say that by pure thought we can understand how the world is put together, because if there's anything we've learned from the history of the past, it's all the surprises that are in store for us. Nothing has been more effective in driving us to these surprises than experiment itself. And yet we've also learned that out of the imagination of man, the feeling for symmetry, the instinct for what is



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beautiful and right and simple, we can make enormous progress. While we must make our way in this world by experiment, our guides, I think, must still be in large measure the philosophers and thinkers of the past.

Time and Space

Q: The religious believer claims that it is possible to transcend these dimensions. I don't know that the space-time concept, like mathematics, is anything more than a way of defining existence and the world. Is it conceivable in physics for something to exist or an event to take place outside space and time?

Wheeler: Einstein speaks somewhere of Leibniz as one of the very few men who preserved his skepticism toward the Newtonian view of space and time. This is a healthy thing to realize, be-

cause it's taken for granted that space-time is what physics tells us it is, a framework for all that goes on. It's astonishing to be reminded that this is really a mental construct we ourselves build up out of our experience.

Q: Can time exist in a void?

Dicke: Time is not something one can measure, like water. I think the nicest way of describing time is to relate it to space. If two bodies collide, their collision can be characterized as happening at a certain place and a certain time. If two other bodies collide, the event might happen at a different place and a different time. But when you try to define the distance and time difference between the events, you find that complicated concepts are involved.

Q: If there were no events?

Dicke: If there were no events, you would be speaking of a universe, if you could conceive of it, that was static. Time would then have no meaning.

Q: Is time always a continuum?

Dicke: This raises an interesting question in relation to order—whether one thing comes after another or before, whether one thing causes another but not vice versa. The question of order is very interesting, because the laws of physics are reversible under time reversal. You would think that under these conditions there would be no way of saying whether something happened before or after because you could measure time in either direction. The only thing we've been able to come up with as a way of distinguishing future from past is the phenomenon of order and disorder. The universe tends in the direction of more disorder, of increasing entropy, so the direction of increasing disorder is the direction of time flow.

Transformations

Q: This word "transformations" has current usage in depth psychology, so we're hearing it a lot. But it comes from the past; all mythologies and religions deal with transformations or a transformation. By this is meant various things: that things or beings change their shape or form in time and space; that one thing becomes another; that everything will someday be different, as after Judgment Day. Physics deals a lot with transformations because physicists agree that the world is in a state of becoming, that things change in space and time. Has this idea led you to further speculation?

Ostriker: Many of the transformations that we know about depend on the

orientation of the observer. One observer looking at a given world will see it differently from another observer even though the world is the same. They can quite honestly see different things. The physical laws are invariant systems, but if you are at different coordinates, you see different things.

Q: But some transformations are not at all obvious. Would one dream, for example, that not only can matter be transformed into energy, but that the transformation is reversible?

Ostriker: You're right. Very often in physics two things are thought to be different, each one preserved as a conserved quantity. Then afterward you discover that they are different manifestations of the same thing and that the sum of these two things is the conserved quantity. So one thing changes into another. It's unexpected when it's discovered. You say, gee whiz, there are fewer things in the universe than we thought.

Q: May we talk about aspects or manifestations, about things that seem different but are really not or are other than they appear to be? Are particles really particles, or are they bits of energy?

Dicke: These are different words being used to describe the same thing. We can only describe the way things behave. Our views of the nature of physical particles have changed. There was a time, not too long ago, when people thought of the proton and neutron and electron as definite particles created at the beginning of the world. One could change into another, but each had a definite separate existence. A more common view now is that a particle is a continually changing form, that it has a complex structure. A neutron, for example, can be thought of as being a neutron part of the time and a proton, electron and neutrino part of the time. It's a very complicated picture with particles forming and reforming, dissolving into one another.

Q: Is there a situation in which things become each other and can no longer be properly individuated or defined?

Dicke: It's not inconceivable that someday we will have a theory that will view all the elementary particles as different states of the same entity, which would then take various forms. We've seen many attempts in the last decades to create a so-called master formula, an all-encompassing theory. These attempts have not been very successful.

Q: What kind of reality do the particles have?

Ruffini: The particles, as they manifest themselves here and now, are absolutely necessary for our view of the universe. The size of the particle appears to us to be related to the size of the universe, to the dimension of the stars and even to our own existence. It seems like a circle: we exist because of the universe, the stars, the sun; and, ultimately, everything exists because of the particles. Yet, we do not think that the particle is the final structure of nature.

Wheeler: The particle is a concentration of energy endowed with all kinds of special properties that set it off from other particles and from energy in the raw. And if there is any mystery that's greater than any other in present-day physics, it's why particles should have this set of unique and characteristic properties. And if that's the greatest mystery in physics today, then it's really an enormous encouragement to think we may someday make progress in understanding this mystery. That is, we may realize that the identity of the particles gets washed out or transcended when these particles fall into a black hole. There's absolutely no way to keep track—by any measurement made from outside the black hole—of what went into it. In this way the black hole symbolically marks the threshold between the world of the individuated and the world of the abstract.

Q: I do not understand the relationship of the particles—the very, very small—to the universe—the very, very large. Why should the same laws work for both?

Wheeler: In the past five years one of the greatest developments in elementary particle physics has been so-called conformal invariance, the discovery that the equations of elementary particle physics possess a property that in effect is this: changing the scale in which you examine the phenomenon does not change the nature of the phenomenon. For decades this so-called conformal invariance has been known to be a property of electromagnetism. The conformal feature of gravitation physics has been known for a lesser time. But the conformal features of elementary particle physics are a discovery of the past five years. This strange feature of nature that permits us to subsume the very large and the very small under the same kind of equation is something we don't yet understand, but it raises in one's mind the perpetual question: Can it be true that what we think of as the very

small and what we think of as the very large are really not so different?

Unity or Oneness

Q: The quest for a unifying principal is as old as recorded history. Why do scientists feel that nature is unified?

Ruffini: Again it's a belief. And the belief holds that there is only one nature, which is completely self-consistent. It is also true that we perceive more and more unity in nature. In this connection the philosophy of Leibniz has been important to our thinking. His theory of monads, for example. It is possible to remove one monad from the Leibnizian universe and from its analysis understand the structure of the universe.

Q: Are you saying that this quest for unity has been as consistent in physics as it has been in philosophy and religion?

Ruffini: Yes, but we have also had tremendous success in our unifying. When Galileo described the motion of a particle, he used a great many brilliant geometrical tricks to make it fit circumstances. Newton's world view was mathematically more sophisticated, and his equations explained in complete generality all possible motions of a system in a space given a priori for any instant of time. General relativity presents us a totally new view of the key ideas of space and time, so it is both more complex and more unifying at the same time. Paradoxically, however, once one understands the new theory, nature appears to be very much simpler.

Q: In experiencing the world, we experience its multiplicity. How then do we get multiplicity out of oneness? Is the oneness manifesting itself in a multiplicity of different ways, among them the very large and the very small?

Wheeler: It really comes back to your question about the power of mathematics. To me one of the most remarkable things is the multiplicity that came out of the Schrödinger equation [the basic equation in modern physics, replacing Newtonian mechanics in the description of atomic phenomena]. It was far beyond anyone's power of thought, Schrödinger's or anyone's, to anticipate the wealth in that one equation. Similarly, I believe that when we discover the equation behind the universe, for a long time we won't realize the multiplicity that's hidden in it. We won't realize how we ourselves fit into it.

I suspect that at present there's nothing hindering us more from getting this equation, the equation behind the uni-

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verse, than the multiplicity we see about us and the gargantuan possibilities that exist for our interacting with these multiplicities. By comparison, it's preposterous to think that one equation, particularly a simple equation, could have everything hidden in it.

Q: I have just read an article in which you use Miës van der Rohe's architectural edict, "Less is more!" and, by analogy, you create a new analogy, "Much into little!"—your description of what happens to matter in black holes. You mentioned Dmitri Mendeleev, the inventor of the periodic table of the elements, and his quest for unity.

Wheeler: How did Mendeleev get to the one, the unity? The poor man was giving lectures in chemistry, and he so wanted his students to get the feel for chemistry. He thought it would help to arrange the elements in some natural tabulation. He searched for ways that would make it easy for his students to understand, and in the process he himself understood. Unity emerged from the search for unity!

Birth, Death, Rebirth or Beginnings

Q: Can you conceive of there being

no beginning and no end?

Dicke: I have trouble with no beginning and no end. If our laws of physics permit us to say what happened yesterday, you would think that they would permit us to say what happened the day before. We ought to be able to continue indefinitely. We ought not to come to the day when we could not say what happened before that. In other words, there should be no real beginning.

Q: You incline toward the "big bang" theory of creation. Where did the big bang come from?

Dicke: Our observations today are not complete enough to give us a certain picture of what happened billions of years ago. The further back you go, the more difficult it becomes to speculate. But despite this difficulty, we have a measure of confidence in talking about what happened only a few seconds after the big bang. This confidence comes from a variety of sources, including the helium content of the sun and stars.

Q: Could there have been a different universe prior to the big bang?

Dicke: I would like to believe so, but we can't find any support for that idea in the theoretical structure.

Q: Could it have happened out of nothing if there had been no particles?

Dicke: This is a real problem because the theoretical structure we have develops a singularity as you go back in time, and our ideas are limited by this theoretical structure. We cannot go back in time beyond a certain point. We have a philosophical reason to believe that you can go back further, but in terms of the formal structure of physics, you can't find a way to do it.

Q: I think that two phenomena are now taken for granted: a continuous complication of matter from the lighter and simpler toward the heavier and more complex elements and a constant interchange of matter so that new stars are perpetually forming from the ashes of stars already dead. Would you say something about this constant death and renewal in the universe?

Dicke: As we see it, the very early universe was so hot that the heavy elements couldn't exist. They would have evaporated into electrons, protons and neutrons. Then as the universe began to expand, it cooled and the hydrogen (the first element that would be formed) reacted with neutrons to form helium. So there was the helium and hydrogen and not much else—a little lithium, a little beryllium. Everything heavier was

Atoms in your body have been through several stars—they were ejected many times as gas from exploding stars”—Ostriker



formed later in the stars.

Q: Will you explain cosmic deaths?

Ostriker: Deaths of stars—that's something I work on all the time. Certainly we know that a lot of the matter in a star is reprocessed at its death. When a star dies, some of the matter collapses with it, but a lot of it is ejected. This matter will be included in the next generation of stars and so on ad infinitum. It's been estimated that atoms in your body have been through several stars—that they were ejected many times as gas from exploding stars.

Q: What transformation has matter undergone in the collapsed part of the star? Would we recognize it as matter?

Ostriker: We know at least three different ways in which stars can die. One way is to form white dwarfs. These are about the mass of the sun and the size of the earth. They're very dense, but they are made up—so far as we know—of ordinary elements. If you could take a cubic inch out and put it in the laboratory, it would be recognizable—the same elements that we have on earth but in different proportions. In neutron stars the surface layers are also recognizable, but the interiors would be quite unlike any

state of matter on earth. In these stars the density is almost unimaginably large: a cube 1/16th of an inch on each side would have a mass of 100,000 tons.

Q: And in black holes?

Ostriker: Speak to John Wheeler about that. At very high densities there are probably particles that we've never seen on earth. It's very bizarre. If you made a bit of a black hole, there would be nothing you could hold it in. It would be tiny, and it would just fall through the earth picking up matter. A one-centimeter black hole would weigh 10^{28} grams, or the mass of the earth, I think.

Q: So in the process of dying, the star liberates energy, or is this too bizarre a way to describe it?

Ostriker: We might have a bit of fun in forming an analogy on that. There have been arguments that evolution is directly influenced by cosmic rays. I think they're interesting speculation. Cosmic rays, according to current theory, come from deaths of stars, exploding stars or supernovae. Thus there might be a direct connection between what is given out at the death of a star and the evolution of life on earth. That blue light in the Crab nebula is unlike

any other kind of light. It's produced by very high-energy particles, cosmic rays in the expanding nebula.

Q: What's making the cosmic rays?

Ostriker: The present theories have it that the pulsar is a little, rapidly spinning star ejecting particles at extraordinarily high energy.

Q: Is this a star that's dying or dead?

Ostriker: Dying, but not quite dead. Unlike a black hole, which is totally dead, this is still giving out enough energy to keep the whole nebula shining.

Q: What happens to the particles after they have fallen into a black hole?

Wheeler: The particle had mass before it entered the black hole. After the black hole has absorbed the particle, its mass has been augmented, and in this respect something remains. The electric charge also remains and a third property as well, angular momentum. But not one other property remains.

Q: So the properties are mass, charge and angular momentum. What precisely are they?

Wheeler: They are in some respect the most primitive features you could have. Andrey Sakharov, the father of the Soviet H-bomb, who is now working in gravitation physics, says in effect that such things as mass and charge—in other words, such things as gravitation—are really about the lowest degree of penetration that one could ever think of having in the structure of nature, rather than the highest. He says that there's a very close analogy between these features of matter and such an everyday feature of matter as elasticity. You throw almost anything together and melt it, then let it cool down and solidify, and you'll find that the structure, complicated as it is, is endowed with elasticity. If you stretch it with a certain force, it will yield a certain amount; how much it yields is a measure of its elasticity. This elasticity is one number that summarizes in itself a wealth of internal complications of the material—whether it's made of tar or diamonds, glue or beeswax. Sakharov says that although the world is a complicated mixture of particles, their properties all add up to a single number, which he calls the metric elasticity of space. It's his name for what gravity is. This grossly oversimplified single number has hidden inside it all the contributions from a wealth of internal structures that we are still so far from understanding.

Q: But wouldn't an attribute such as

elasticity be very primitive?

Wheeler: In 1953 I first began to take seriously Einstein's vision that everything is made out of curved empty space, that particles are constructs out of this magic dough, which is geometry. Sakharov says in effect that it's as crazy to think of particles as made out of geometry or out of curved empty space as it would be to think of atoms as made out of elasticity.

We learned from Mendeleev's periodic table that to think of sulfur and chlorine or carbon and hydrogen in terms of their particularities—as requiring their own separate laws, structures, valences—was the wrong way to understand matter. We learned that all these particularities of nature went back to one simple, more primitive view of electrons held together by electric forces and moving in accordance with the quantum principle. If we try to guide ourselves by this analogy, we would say it's exactly wrong to think of the particles as a primitive world. There must be something far simpler out of which they themselves derive their structure, and that something far simpler—call it pregeometry or what you will—is the thing to which we are at present directing our attention.

Q: So pregeometry, or whatever it will be called, might be the magic dough or building material of this world. The end of the world is anticipated by the existence of the black hole, a star having undergone gravitational collapse. This phenomenon is an invisible omen of our future, you've said, because gravitational collapse is the ultimate destiny of the universe. But you have also suggested that this end will become a new beginning—that something else, something new and different, will be reborn from the ashes.

Wheeler: I am thinking of the oriental concepts of reincarnation and of cycle after cycle, not only of man, but of the universe itself. I would be the last person to know how to analyze this kind of idea in a sensible way. I do, however, feel that in this game of the collapse of the universe, we're very far from having a cycle that leaves room for any individuality to remain. In fact, we have come to the point where the very ideas of "before" and "after" are inappropriate. The very idea of time is an approximation. Of all places it goes wrong, it goes most wrong at the moment of actual collapse. Although we don't know how to deal with the physics of that col-

lapse, we've had experience with other kinds of physics that have many points of analogy with it.

By the predictions of the old classical physics, when an electron collides with an atomic nucleus we would arrive at a catastrophic infinite energy at a physically finite time. But we know today from our experiments that the electron is scattered rather than annihilated. So we can think of the universe itself as starting a new cycle, or we can think of different histories of the universe, each with its own number of particles, length of time, maximum contraction, possibilities for life or nonlife.

Q: Can you construct a more ordinary analogy?

Wheeler: Yes, I can believe that any given cycle of the universe is put together out of elements—Lord knows what they are—much the way a broom is put together out of bits of hay. Then we follow these bits of hay up to where they meet at the handle of the broom. So, you could think of following the phases of the universe down to the point of minimum dimension, until everything collapses. But then instead of thinking that a new form must begin at this point, it could be that at this point of maximum contraction something quite disorganized happens. Bits of hay blow about in the wind, lacking any organization whatsoever. The options must be fantastically varied.

Human Beings

Q: At the beginning of these conversations we spoke about human intuition and man-made mathematics in order to find the door through which we enter the universe and its particles. But we, the observers of the universe, are also constructed out of its particles. What role do human beings play in this strange enactment of nature?

Wheeler: No theory of physics that deals only with physics will ever explain physics. I believe that as we go on trying to understand the universe, we are at the same time trying to understand man. Today I think we are beginning to suspect that man is not a tiny cog that doesn't really make much difference to the running of the huge machine but rather that there is a much more intimate tie between man and the universe than we heretofore suspected. Only as we recognize that tie will we be able to make headway into some of the most difficult issues that confront us. Nobody thinking about it from this point of view

can fail to ask himself whether the particles and their properties are not somehow related to making man possible. Man, the start of the analysis, man, the end of the analysis—because the physical world is in some deep sense tied to the human being.

The framework for this loop, the thing that gives it structure, is pure mathematics. Or the framework for this loop is pregeometry. Give it whatever name you will, it provides a channel, a structure, a tie by which we progress deeper and deeper into the analysis of nature from elastic bodies to atoms, from atoms to nuclei, from nuclei to elementary particles—and as we press further on, we'll come back, in some strange way, to man himself.

Q: Can you characterize our relationship to the physical world at this moment in time?

Wheeler: Insofar as we've learned to understand the quantum principle, it's the small tip of an iceberg that tells us that the momentum and the position of an electron are not qualities that exist independently of us but depend upon our consciously making a decision to measure the position and the momentum in order to bring these features into evidence. I think that through our own act of consciously choosing and posing questions about the universe we bring about in some measure what we see taking place before us.

Therefore, I think the word "observing" is inadequate. A better word is "participation." We are going to come to appreciate that the universe itself in some strange way depends on our being here for its properties. "Depends" is perhaps not the right word, because it implies that the universe is dependent upon us, when there is a mutuality of relationship that needs to be stated.

There's one term I love to give the universe just as a temporary symbol because every day one needs a new flag to run up on the mast to guide one's work. The flag that I like to run up just now is called "Our Participatory Universe." [E]

ANNOUNCING ID'S NAKED SINGULARITY CONTEST

An Impossible Challenge
to the Imagination
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