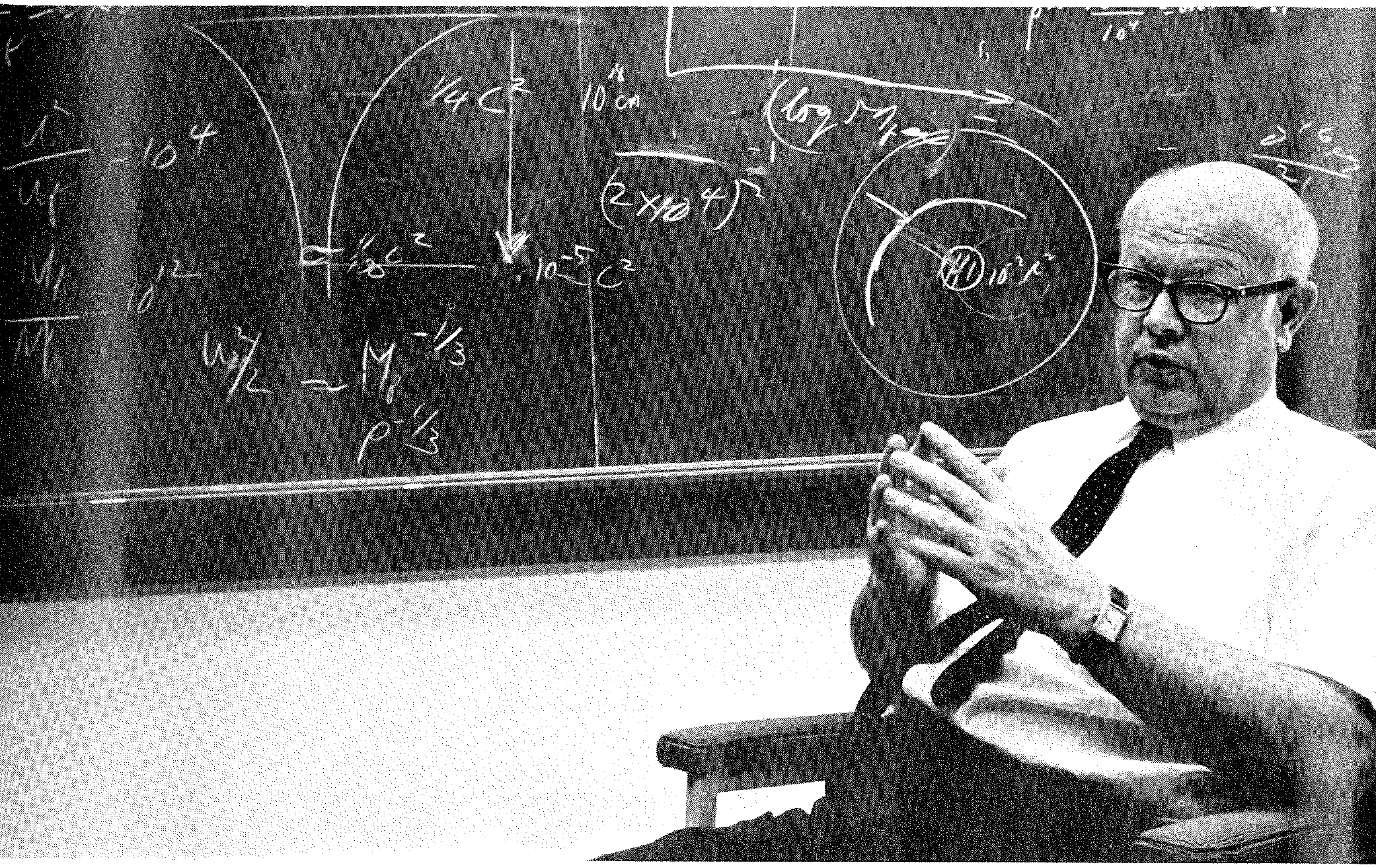

THE EXCITED UNIVERSE

by William A. Fowler

A progress report on studies at Caltech and elsewhere on the frontiers of astronomy and astrophysics.

All of us have looked up at the sky on a dark, clear night. If we watch awhile, the stars seem to march steadily and majestically across the sky; the starry heavens appear serene and calm. Nothing could be farther from the truth! Telescopes and other instruments—on the ground, in balloons, in rockets, and in satellites—reveal to the astronomer and the physicist quite another picture, a picture of an excited universe in which exploding stars and exploding galaxies play dramatic and important roles.

A revolution in astronomy and astrophysics has taken place since World War II. In this period, optical astronomy—the study of ordinary light from celestial objects—has made great progress. But even greater progress has

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been made in other fields. It has been found that celestial objects emit radiation all across the electromagnetic spectrum—radio waves, infrared waves, x-rays, and gamma rays. Radio waves and infrared waves have longer wavelengths and lower intrinsic energy than ordinary light waves. X-rays and gamma rays have shorter wavelengths and higher intrinsic energy.

The principal heroes of this revolution have been the radio astronomers. The discovery of radio emission from galaxies, from the starlike objects called quasars, and from the newly discovered objects called pulsars has opened up a new era in astronomical observations and theory. We work very hard in our terrestrial nuclear and atomic laboratories to understand what is going on in the excited universe, but so far our ignorance is matched only by our bewilderment. This, then, is a progress report on studies at Caltech and elsewhere on the frontiers of astronomy and astrophysics.

All of these new and exotic radiations involve the emission of energy from atoms and nuclei or from swift electrons moving in strong magnetic fields. They represent the methods by which objects in the excited universe are de-excited—methods by which their apparently enormous supplies of energy are released into the vast reaches of space.

One of the principal questions raised by all these new observations is: What is the ultimate source of energy for these prodigious emissions of radiation? Is it nuclear energy, gravitational energy, or some new and unknown source of energy?

Nuclear energy is the basic source of power in ordinary stars. Stars are born, evolve, and come to a variety of untimely ends. During their lifetime, they shine on energy generated by the process of nuclear fission. Stars are truly nuclear furnaces.

The way in which stars operate as nuclear furnaces is one of the most exciting and important problems in science today. There are two reasons why. One, we know that nuclear fusion processes generate the energy which makes stars shine with an enormous output of light and heat. With our nuclear reactors we have successfully harnessed what we call nuclear fission, but we have not succeeded in putting nuclear fusion to work. We can study fusion in our laboratories, but so far we just cannot make it work on a practical scale as a source of power. Thus our studies of the nuclear fusion that takes place in the sun and other stars have long-range implications for all of us.

There is a second reason. Nuclear processes generate energy by changing one elementary form of matter into another. We often speak of these processes as the "transmutation of the elements." This was the age-old dream of the alchemists, and in the 20th century this dream has come true. In our laboratories we can change one element to another on a small scale, and in our fission reactors on a large scale.

On a far grander scale, fusion is transmuting elements in the stars. This has led us to the belief that perhaps all of the heavier elements, such as carbon, oxygen, iron, lead, and uranium, have been built up in stars from the lightest of all the elements—hydrogen—which we take to be the primitive material with which the universe began.

Let us now examine the role played by stars and galaxies in the generation of energy and in the creation of new elements.

Many of the observations on the astronomical universe have been made with the magnificent 200-inch telescope on Mount Palomar. The largest systems seen with telescopes of this type are called clusters of galaxies. If you look in the direction of the constellation *Virgo*, but far back of it, you see the Virgo Cluster of associated galaxies. Our own galaxy, the Milky Way, is in the so-called local group, which contains 16 other galaxies. Unfortunately we are imbedded in our own galaxy so we can't get an over-all view, but we know that our galaxy looks very much like its twin, the spiral Andromeda Nebula. Also unfortunately, we can't even see the center of our galaxy because of the large amount of obscuring gas and dust between us and the center.

Here I want to emphasize the exchange of matter between stars and the interstellar medium, which is filled with gas and dust particles. It is in the stars that the nuclear reactions by which energy is generated are taking place. It is in the stars that element synthesis takes place—the transmutation of one elementary form of matter into another.

It is in the interstellar medium, once this material is ejected by some kind of explosive phenomena, that the mixing takes place. Then, eventually, when new stars are formed by condensation, they not only contain the primordial hydrogen of the interstellar gas and dust but also contain the nuclear debris of the processes that have taken place in stars of previous generations.

What is the evidence that stars form? And what is the evidence that stars explode?

Evidence that stars form from the interstellar medium can be seen in the nebula in the constellation *Sagittarius*, located in our galaxy. This nebula of gas and dust is being illuminated by bright stars embedded in it, and it is reflecting light into the telescope and into our eyes. It is always in regions where there is a great deal of material from which stars could be formed that astronomers find the newly formed stars, which can be very bright—so bright, in fact, that they are exhausting their nuclear fuels on a very short time scale. This means that they must be young.

With this indirect evidence, namely that young stars are always found associated with great clouds of gas and dust, we believe that stars are forming in the galaxy all of the time and have been since the formation of the galaxy itself.

So now stars have formed. What happens to them?

Our galaxy looks very much like its twin, the spiral Andromeda Nebula. If our solar system were located in Andromeda, we would be somewhere halfway out from the central nucleus, nestled in the inner edge of one of the spiral arms.

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Just imagine that we are down deep in the interior of the sun, where the temperature is something like 15 million degrees. We know that the sun consists primarily of hydrogen and helium, with some mixture of heavier elements—only about 1 percent in total—which has been produced in previous stars. We are uncertain concerning the origin of the sun's primordial helium. It may have been produced in previous stars, or it may have been produced in the "big bang" at the beginning of the expanding universe.

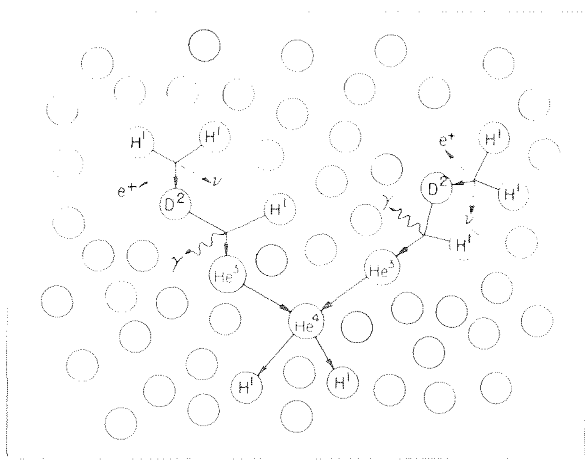
Because of the high temperature, all the nuclei and electrons are moving at high velocity, and two hydrogen nuclei, called protons, can collide at these high velocities. When they collide, we know that positrons and neutrinos are emitted. The main point, however, is that the nucleus of the heavy isotope of hydrogen, the deuteron, is formed. The deuteron has mass 2 on the scale used in nuclear physics. On this scale, the proton has approximately the unit mass or mass 1. The deuteron takes up the motions of the other nuclei and electrons, and eventually a deuteron collides with another proton. We know, from a reaction which we can study in detail in the laboratory, that when a deuteron and a proton combine with the emission of gamma radiation, they form a nucleus of mass 3, which turns out to be an isotope of the element helium, the second element in the periodic table.

For many years we didn't know what happened to the He^3 nuclei because they don't interact strongly with protons, and the deuterons are consumed mostly by their interaction with protons. We know from laboratory experiments that He^3 can collide with another He^3 produced in exactly the same way to form He^4 with two protons being given off. So six nuclei of hydrogen unite to form helium, and we get two of them back. The over-all result is that four hydrogen nuclei have been changed into a helium nucleus, and at the same time that this has been taking place energy has been generated. The mass balance is almost exact, but not quite. The He^4 weighs a little less than the four hydrogen nuclei, and by Einstein's principle, $E=mc^2$, the mass lost is converted into energy. In practical units, a pound of converted hydrogen gives 100 million kilowatt-hours of energy.

We have to work out detailed processes like this in the laboratory to tell astronomers some of the facts about the processes which they can use in their calculations of energy-generation and element-transmutation in the stars.

Actually this is a very old story. It was in 1920 that Arthur S. Eddington first suggested that the conversion of hydrogen into helium is the source of energy in stars. In 1920 Eddington's critics—and he had many of them because he was an outspoken man—pointed out to him that all these hydrogen nuclei are positively charged, and thus they electrostatically repel each other. They argued that even at the center of the sun the temperatures are not high enough that the hydrogen nuclei will have velocities great enough to overcome the electrostatic repulsions and thus form the deuterons and the He^3 and the He^4.

In 1920, when Newtonian mechanics was still the basis of physics, Eddington didn't



The fusion of ordinary hydrogen in the sun.

know the answer, but he had enough faith to give this reply to the critics: "We do not argue with the critic who urges that the stars are not hot enough for this process. We tell him to go find a hotter place."

Eddington's critics were saved from their fate by quantum mechanics, which tells us that even though the electrostatic barrier between two positively charged particles is a very great one, there is a finite probability of penetrating this barrier and forming compound systems.

To show how close the ancient Greeks were to these ideas, this is what the Greek philosopher Leucippus is reported to have said more than 2,500 years ago:

> They [atoms] move in the void and catching each other up jostle together, and some recoil in any direction that may chance, and others become entangled with one another in various degrees according to the symmetry of their shapes and sizes and positions and order, and they remain together and thus the coming in being of composite things is effected.

I don't know if we have really learned very much in the last 2,500 years or not. But the essential difference between the Greek philosophers and us is the fact that we can do experiments which show that these transmutations of the elements really come about.

In our laboratory at Caltech we use five electrostatic accelerators. In such devices we accelerate nuclei to velocities as great or even greater than they have in stars, and we study the details of the nuclear transmutations produced when these high velocity particles collide with stationary "target" nuclei.

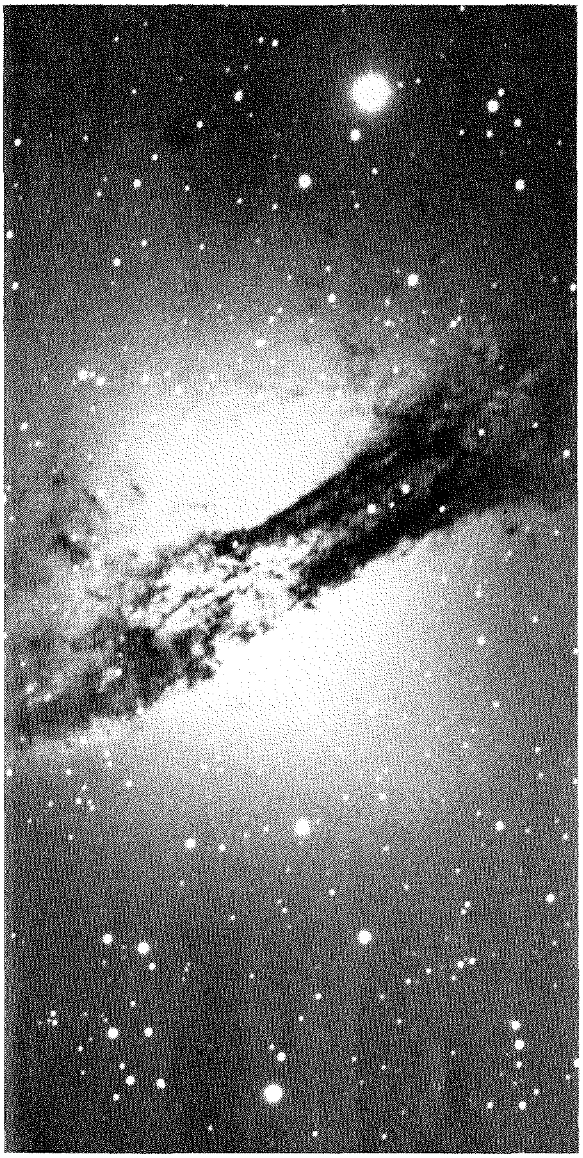
Now let us examine the idea that stars can eject their nuclear debris back into the interstellar medium. The most spectacular shape of this is the Crab Nebula, seen in the direction of the constellation *Taurus*. It is famous for the fact that in 1054 A.D. Chinese astronomers saw a new star appear where we now see the Crab Nebula. (We call these phenomena supernovae; they had a delightful term for it—"guest star.") And in the intervening period of 914 years the explosion has moved the material out from the central region. If you measure its velocity and size, you can show that in 1054 all of this material was back in a compact form—a star! We see no evidence for the central star that exploded, so presumably the whole star was disintegrated.

The Crab Nebula is the prototype of those celestial objects from which we can detect radiation from all across the electromagnetic spectrum. Radio astronomers find strong radio waves coming from the Crab, mostly from an extended region very close to the center. X-rays and gamma rays are also observed.

In addition to the luminous material, we think there are fast electrons moving in great spirals in the magnetic fields which thread all the nebula. And we know that electrons moving in the magnetic fields give off what is called synchrotron radiation—just as the electrons that we accelerate in our synchrotron accelerators give off radiation. This radiation covers the entire spectrum from radio waves through visible waves into the x-ray and gamma-ray regions.

The Crab Nebula, which consists of the expanding debris of a supernova that appeared in 1054 A.D., is the prototype of those celestial objects from which astronomers can detect radiation from all across the electromagnetic spectrum—radio waves, x-rays, and gamma rays.

There have been three supernovae in our own galaxy in the last 1,000 years—the one in



The elliptical galaxy Centaurus A is typical of what the optical astronomer finds at the point where the radio astronomer says there is a source of radio emission. This is a mixture of 1,000 million stars. Some catastrophic event produced the dust lane which circles the galaxy. The radio-emitting region of this galaxy is enormous compared to the size of the galaxy itself.

1054 observed by the Chinese, one in 1572 studied by Tycho Brahe, and one in 1604 studied by Johannes Kepler. Nowadays we see supernovae mostly in galaxies other than our own. In 1966, ten supernovae were discovered, so we can and do study supernovae occurring frequently—10 to 20 a year—in other galactic systems.

Caltech's radio telescopes, in the Owens Valley in California, are used by radio astronomers in somewhat the same way a human being uses his ears—to pinpoint the location of the radio emissions from outer space. Because of the instruments in locations all over the world—in Australia, England, Holland, Russia—radio astronomers can tell the optical astronomer, "There is a source of radio emission. Look and see what you can find there."

Typical of what the optical astronomer finds at the point where the radio astronomer says there is a source of radio emission is an elliptical galaxy called *Centaurus A,* observed in the direction of the constellation *Centaurus.* It has always been known that this galaxy is rather strange—a mixture of 1,000 million stars with a great dust lane that circles the galaxy and which is absorbing the light. Some type of terrific catastrophic event which happened in its history produced this dust lane and the radio emissions. The radio-emitting region of this galaxy (a galaxy comparable in size to ours) is enormous compared to the size of the galaxy itself.

The electrons and magnetic fields were ejected perpendicular to the obscuring material which forms the dust lane, and now synchrotron emission in the form of radio waves comes from two patches above and below the plane of the dust lane.

Even these radio galaxies are not the most exciting things that the radio astronomers have found. They also found the quasi-stellar objects called quasars. They are radio sources which, when viewed by the optical astronomer, look very much like a star. When the optical astronomer looks carefully at quasi-stellar objects, he finds they all show a very large red shift. That is to say, the optical lines which the astronomer sees in the emission from the object are shifted to the red in color.

The kind of evidence astronomers have gotten from studying the red shift of ordinary galaxies led to Hubble's Law: The more distant the object, the greater the red shift of its radiation. Previous to the discovery of the quasars this had only been found in galaxies. But with the discovery by Maarten Schmidt of Caltech of the quasi-stellar object, red shifts many times greater than are found in the most distant galaxies have been found in the quasi-stellar objects.

One of the most distant quasi-stellar objects that has been found so far is 3C191 (which means it is the 191st object in the third catalog of the Cambridge Radio Observatory in England). In its spectrum the lines of hydrogen and carbon are shifted to the point where their wavelength is three times that of the wavelength of the corresponding light that we can study in the laboratory. This means that the red shift is about 2, whereas all of the galaxies that have been studied previously have red shifts of, at the most, 3 to 4.

So, on the basis of the interpretation of the red shift (and this is not accepted by everyone) as implying greater distance, these quasi-stellar objects are the most distant things that we find in the universe. And being very distant means that in order to give the amount of radiation which we receive, they intrinsically must be pouring out a great amount of radiation at their sites.

We would all be very skeptical of this if it wasn't for the fact that with the discovery of the quasars optical astronomers began to look at strange systems, such as the galaxy called M82. By studying M82, Allan Sandage of Caltech was able to show that there was an explosion in it, something like five million years ago, and the total amount of material ejected is something like five million times the mass of the sun.

We know, intuitively almost, that the large amounts of energy involved in the quasar emissions must involve large masses that have been ejected from some kind of an explosive, violent event in the galaxy.

Five years ago Fred Hoyle, Plumian Professor of Astronomy at Cambridge, and I were thinking of where the energy comes from that throws out this enormous amount of gas, and we came up with the idea that nuclear reactions couldn't possibly do it and that perhaps it was gravitational collapse, followed by explosion of the outer material around a central, imploding, gravitationally collapsing core. I talked about it at a meeting of the American Physical Society, and afterwards reporters talked to me. Two weeks later I picked up *Time* magazine (February 8, 1963) and read: "Astrophysicists Hoyle and Fowler from Caltech told the American Physical Society that galaxies *often* explode with *improbable* energy."

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You may think that all I have told you is highly improbable. This could well be true. But there has recently been a discovery which seems more improbable. Radio astronomers at Cambridge, England, have just observed radio pulses at several points in the sky which come in remarkably steady periods of the order of one second. For one of the pulsing sources, or pulsars as they are called at the moment, the period has not varied by one part in one million over the six months since its first detection. It is almost certain that these pulses arise somewhere in our galaxy but definitely from outside the solar system. Numerous suggestions concerning the nature of the pulsars have already been made. Some think that the pulses come from vibrating white dwarfs, which are very small, very dense stars, or from vibrating neutron stars, which are even smaller and even more dense. There are even those—and I refer to respectable scientists—who think that the pulses represent signals from some advanced civilization somewhere in the galaxy. But in any case, here is one more example—a very current one—of the *excited universe* I have been talking about.