Radio "Stars"–Explosions In Space

by Jesse L. Greenstein

The field of radio astronomy has had an extremely rapid growth. First, weak signals from our own Milky Way Galaxy were detected with instruments of low resolving power; then refined and sophisticated devices of high resolving power began to locate radio sources at various points in the sky. The first of these sources to be identified was a galaxy 500 million light years distant. The entire northern sky has now been mapped by the group under Martin Ryle at Cambridge University, and catalogs of a thousand such sources have been prepared. Various workers at the Caltech Radio Observatory (notably Tom Matthews, Per Maltby, and Alan Moffett) have been responsible for great improvement in determining the accuracy of the positions of these sources, and – collaborating with optical astronomers – in identifying the sources with optical objects.

Three years ago there was considerable surprise when, for the first time, accurate positions, combined with accurate measurements of the apparent angular diameter of some of the radio sources, indicated that a few extremely small objects had been found. Radio galaxies had been characteristically several minutes of arc in angular diameter, but these new objects were less than a few *seconds* of arc in diameter.

Refined work at radio observatories at Caltech, in Manchester, England, and in Australia revealed that these objects were probably less than a second of arc in diameter. Sophisticated interferometers were used in this research, which showed that relatively simple and inexpensive antennae, separated by distances that were extremely large compared to the wavelength used, could provide better positions and angular resolution than any very large, single, steerable paraboloid that can now be built.

A further surprise came from the failure of Tom Matthews at Caltech to find an obvious identification on photographs of these objects that had been located accurately by radio techniques. Within the accuracy of the positions given, which had become increasingly accurate with time, there was no galaxy or group of galaxies, no emission nebula, no remnant of an exploding supernova to be found. Instead, only relatively faint stars were seen on the photograph.

The first of these to be recognized, 3C48, caused a flurry of excitement two years ago when spectra taken with the 200-inch Hale reflector by Allan Sandage, Guido Munch, and myself, showed no recognizable features. To spectroscopists, this was a direct insult, since in no other objects except supernovae are there lines of unknown origin.

These radio stars produced theoretical excitement also. Analysis by Matthews and Sandage of their brightness, measured photoelectrically at several different wavelengths, gave colors unlike those of other stars. Their distribution of energy with wavelength had no resemblance to the light emitted by heated gases or solids, the so-called black-body distribution. In fact, the synchrotron emission process that produced the radio frequency energy of distant radio galaxies seemed to produce the light of these stars. Very high-energy electrons were present, spiralling around magnetic lines of force and emitting what is called synchrotron radiation. Synchrotron radiation has a distribution with wavelength that is easy to distinguish.

3C48 was the first of these radio stars to be investigated spectroscopically, and Maarten Schmidt followed up the study of these small radio sources last year with even more baffling results than had been obtained on 3C48. In two more sources, whose continuous spectra were probably caused by synchrotron radiation, weak emission lines were seen which again could not be identified.

I studied 3C48 extensively on long-exposure spectrograms taken at Palomar. The mystery seemed to be partially solved, but the solution was tantalizingly incomplete. Three weak, broad, emission lines were at approximately the right wavelengths to be ionized helium and five-times-ionized oxygen. But other observed lines did not fit; and, if helium and oxygen were present, lines were missing that should have been present.

Consequently, although with some hesitation, I developed an elaborate theory which ended up with 40 pages of manuscript, approximately 100 equations, and a suggested explanation. The hypothesis was that 3C48 was the remnant of an old supernova. After hundreds of thousands of years the exploding gases would long ago have vanished into interstellar space, but a star of high density would remain, with unusual composition, high surface temperature, and a source of energy in radioactive decay of some of the elements synthesized in the explosion. Sandage had found near 3C48 and one other object faint wisps of what might be gas clouds too faint for spectroscopy (possibly the remnants of the explosion, according to my hypothesis). This beautiful fantasy neared publication — not proven, and not quite acceptable.

Three puzzles

Fortunately, circumstances and nature intervened. In two other radio stars the emission lines detected by Maarten Schmidt were not at the same wavelengths as in 3C48. If these radio stars were really stars, they constituted a group of three strange objects, all of which contained different lines largely of unknown spectroscopic origin. One puzzle is bad enough. Three similar puzzles with all different features was too much.

Nature, by a freakish accident, had one kind surprise left for us which led to the correct interpretation. One of the recently discovered radio stars, 3C273, is located far enough south to be observable by radio astronomers using the new 210-foot dish in Australia. They found that the object was occulted by the moon on several occasions. From the change in brightness as the moon hid the radio source, and later as the radio source reappeared from behind the moon's rim, they were able to obtain an extremely accurate position and to prove that the radio source was double, and small. One component is only a few seconds or less in diameter, and separated by about 20 seconds of arc from a larger object.

Maarten Schmidt, studying a 200-inch photograph, found a thirteenth-magnitude star with a faint wisp nearby, a jet of nebulosity. The star and the jet agreed almost precisely, within one second of arc, with the positions given by the Australian radio astronomers. When Schmidt obtained the first spectrum of 3C273 it showed a bluish continuum — possibly, in part, of synchrotron origin — on which was superposed a set of rather broad but regularly-spaced emission lines. They looked so much like the harmonic series of lines produced by hydrogen that it seemed plausible that they were produced by some atom resembling hydrogen. The wavelengths, however, disagreed with those of the hydrogen lines. Schmidt and I attempted to explain them as an element with a single electron left near its ionized nucleus, and therefore having the regular simple spacing of the hydrogen series.

This effort proved to be vain. The only rational solution was that, if it was a hydrogen-like atom, it was hydrogen itself. The wavelengths, however, were 16 percent larger than those of hydrogen. The decisive point was an observation by J. B. Oke, with an infrared photoelectric scanner. Oke found a single strong emission line in the near infrared, at wavelength 7560 Angstroms. The infrared line proved, in fact, to be H-alpha, the first line of the hydrogen spectrum, which is normally at 6563 Angstroms but is here shifted to a 16-percent-longer wavelength, just as were the lines observed by Schmidt.

Another line in the spectrum of 3C273 was then identified as a shifted forbidden line of doubly-ionized oxygen. (Forbidden lines are certain weak lines emitted in a gas at low density.) But at the very violet edge of the spectrum, near the absorption produced by the ozone layers of the earth's atmosphere, one additional line remained. Subtracting 16 percent from the measured wavelength, we obtained the true wavelength as 2800 Angstroms.

This rang an immediate bell. The ultraviolet spectrum of the sun had been observed from rockets years ago by scientists at the Naval Research Laboratory who were pioneers in the ultraviolet spectroscopy of astronomical objects. They found a strong, double, emission line at 2800 Angstroms, the strongest atomic transition in ionized magnesium.

Two possibilities

That a normal star could have a velocity of 48,000 km/sec and show hydrogen and ionized magnesium emission seemed improbable indeed. Normally, stellar velocities are a few tens of kilometers per second. The possibilities remained that we had (1) an extraordinary new kind of star, producing a very large red shift — a shift of lines of the spectrum toward the red end, indicating that objects are rushing away from our stellar system — caused by the action of an intense gravitational pull on light, or (2) a galaxy.

3C273 now had a spectrum that could be explained. It was a simple spectrum and hydrogen was dominant. But its lines did not fit those which I had suspected were in 3C48. Moreover, the existence of a strong line at 2800 Angstroms suggested that I should see whether the strongest line in 3C48, located at 3832 Angstroms, could possibly be the same element with a different red shift. This suggested a red shift of 37 percent. Trying 37 percent red shift on the other lines of my spectrum gave the final answer to the puzzle. Unwillingness to accept the implausible and improbable had made me unwilling to imagine so large a red shift. But now all the strong lines in the spectrum were identifiable. They turned out to be forbidden lines of ionized neon and oxygen. Hydrogen, if present, is weak, unlike 3C273.

The actual red shift of 3C48 turned out to be about 37 percent. If the red shift is due to recession, this is a speed of 110,000 kilometers per second. It is the second largest red shift known, surpassed only by the very faint radio galaxy 3C295, identified by Rudolph Minkowski. Based on current estimates of the size of the universe, a red shift of 37 percent corresponds to a distance of about 5 billion light years; 3C273 is at a distance of approximately 2 billion light years.

The brightest objects

The radio stars, if they are distant galaxies, are enormously luminous. From the observed red shift and apparent brightness, they have approximately the same intrinsic luminosity – about 100 times greater than that of our own galaxy. This is far greater than the luminosity of any other known galaxy. Even in searching over clusters of galaxies which form a large sample of the objects in the universe, the brightest objects found remain approximately 30 times fainter than the two radio stars 3C48 and 3C273.

The interpretation of these two objects as very luminous galaxies involves difficulties and problems. They had first been recognized by radio and optical means as "stars" from their small angular diameter. But the small angular size, at these enormous distances, is not small *linear* size. For example, one second of arc, the upper limit of the size of the apparently stellar image of 3C48, corresponds to 25,000 light years. Since 3C273 is double, the angular separation between the star and the jet corresponds to 150 thousand light years. The faint wisps originally interpreted as remnants of a stellar explosion in our own galaxy are objects of truly galactic dimensions. But they still do not look like normal galaxies.

Is it possible that we are wrong and that they could be stars with an enormous red shift? Obviously, velocities of 110,000 kilometers per second are impossible for stars bound to our own galaxy, in which the maximum speed is about 300 kilometers a second. However, a very interesting state of very dense matter involving both general relativity and nuclear physics might occur in a star of very high density. The possibility exists that red shifts may be caused by the gravitational pull on light, as was predicted by Einstein. In the sun, the Einstein shift is less than a kilometer a second. If we could increase this effect of gravity, the red shifts might become large.

Physicists have found that it might be possible for massive small objects to be stable; a star could weigh more than the sun and have a radius of only 10 kilometers (while our sun is 700,000 km in radius). The density would then be about 10 billion tons per cubic inch. For such an object the gravitational red shift would give a recession velocity of about 61 percent the velocity of light.

I fear, however, that astronomical objections to the interpretation as superdense stars are too serious. The thickness of a gas cloud around the star would be needed to produce the emission lines. If it were more than a few kilometers thick, the gravitational red shift would vary inside the cloud and the emission lines would be broadened. Since the lines are relatively narrow, the actual thickness of the emitting gaseous envelope works out to be only a fraction of a kilometer. From the theory of emission lines in hot gases, it proves absolutely impossible to produce an observable emission line in so small a volume. In fact, the emission produced is so weak that these objects would have to lie inside the solar system. Thus, for the present, we must regretfully abandon the hope of finding these extremely dense stars.

An exciting result

We are left then with the still very exciting result that two stars – 3C273, studied by Schmidt and by Oke; and 3C48, studied photometrically by Sandage and Matthews, and spectroscopically by myself – are galaxies of enormous brightness, at very great distances.

Future prospects opened by this discovery are most exciting. We have learned how to find objects of greater luminosity and distance than the most luminous galaxies known till now. If an object like 3C48 could be found at a distance three times greater, it would still be detectable by the radio astronomers who are making surveys of the entire sky. It would emit enough radio noise to have its diameter measured and its position accurately determined by the sophisticated interferometer techniques at the Caltech Radio Observatory. It would be easily photographable and its spectrum could be observed at Palomar.

A red shift of 37 percent is far below the maximum observable for such objects. At three times the red shift of 3C48, the strong ionized magnesium line at 2800 Angstroms, originally in the far ultraviolet, would have moved to 6000 Angstroms, near the red sensitivity limit of photographic plates. It might be followed even further with a photoelectric scanner for the near infrared such as was used by Oke.

If objects still further could be found, we might lose the magnesium emission line found in 3C48 and 3C273 into the unobservable infrared. But we could hope to find, at a much larger shift, the strongest resonance line of hydrogen, Lyman-alpha, which could then be a very strong emission feature at the ultraviolet end of our spectrum. Consequently, if nature provides us with similar enormously bright galaxies, we may be able to trace them very nearly to the horizon of the universe, when the apparent velocity approaches that of light.

The story of the radio "stars," which are very luminous galaxies, is just at its beginning. I have attempted to give our first results, but many important theoretical problems remain. For example, the continuous radiation emitted is not that of the stars in a distant galaxy but it is almost certainly the synchrotron emission of electrons in magnetic fields within that galaxy. The process requires electrons of energies up to 100 billion electron volts moving in magnetic fields near 1/1000 of a gauss.

The masses of gas involved in producing the emission lines, and possibly part of the continuous spectrum, lie in the range between one million and one billion solar masses. The extraordinarily high luminosity cannot be maintained very long. It is almost certain that we are viewing the end-product of a violent explosion of unknown origin which occurred not many hundreds of thousands of years ago, in the time frame of reference of these galaxies. The objects that we are viewing are now long dead, because of the long light-travel time. Schmidt's discovery of an isolated jet in 3C273 at a distance of over 150 thousand light years from its galaxy, requires a duration of the explosive phase of that order of magnitude even if the jet was expelled at nearly the velocity of light.

Recent speculations by Hoyle and Fowler concern the possible brief existence of stars weighing a hundred million times as much as the sun. They have imagined that a star of such enormous mass begins to form out of gas near the center of a galaxy. It is too massive to be permanently stable. There is controversy concerning difficult points in general relativity and neutrino physics as to whether these objects can be stable at all. Some think that they would disrupt before collecting such enormous masses. However, relativistic effects and the production of positron-electron pairs might make stability possible. After a short time, the end product of these large stars would be a collapse and an enormous explosion, which might result in the phenomenon we have here observed.

The jet and the wisps of gas near 3C48 seem to have been blown out nearly at the velocity of light in some initial explosion. The entire galaxy of stars is now invisible, submerged by synchrotron emission from high-energy electrons and magnetic fields which may be the result of such an explosion. In another hundred thousand years the visible remnants of the explosion will fade, leaving only the optical galaxy, possibly profoundly disturbed by this event. It is possible, but far from certain, that we will then have a typical large radio source such as those that have been recently studied at Caltech.

With or without any theory of their origin, it is obvious that the radio "stars" are a valuable tool for cosmology, and one of the most dramatic events in the evolution and life of a galaxy.

Another fascinating facet of this new observation is that we can study now, for the first time, emission lines from the far ultraviolet, which would be unobservable without these large red shifts. One may hope that ultimately they will be observed in nearer galaxies from outside our atmosphere. But it is interesting to note that these two radio stars are too faint to be observable by the first few generations of orbiting astronomical observatories. The magnesium lines had been seen, before this, only in spectra of the sun observed from rockets. One line recognized in 3C48 proved to be a special type of "auroral" forbidden line of quadruply-ionized neon, which cannot be observed in the laboratory or in any astronomical object.

Earthbound astronomy, radio and optical, has shown that it is still very much alive. The universe always is and always will be full of the unexpected.