Are Black Holes Necessary?

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"TO LISTEN TO Cristoforo Colombo, sitting in a dimly lit favorite tavern with a glass of port, recounting his adventures and describing vistas of far lands never seen before, must have made an exciting, unforgettable evening," wrote the editors of the proceedings of the first Texas Symposium on Relativistic Astrophysics, which was held in December, 1963. "But one might doubt if this could ever match the strange fascination of an evening with the late Walter Baade from the Mount Wilson and Palomar Observatories. For more than a quarter of a century he had worked with the biggest optical telescopes on Earth. . . . Baade saw the mysteries of the universe as the greatest of all detective stories in which he was one of the principal sleuths. . . . He told us one evening the story of Cygnus A.

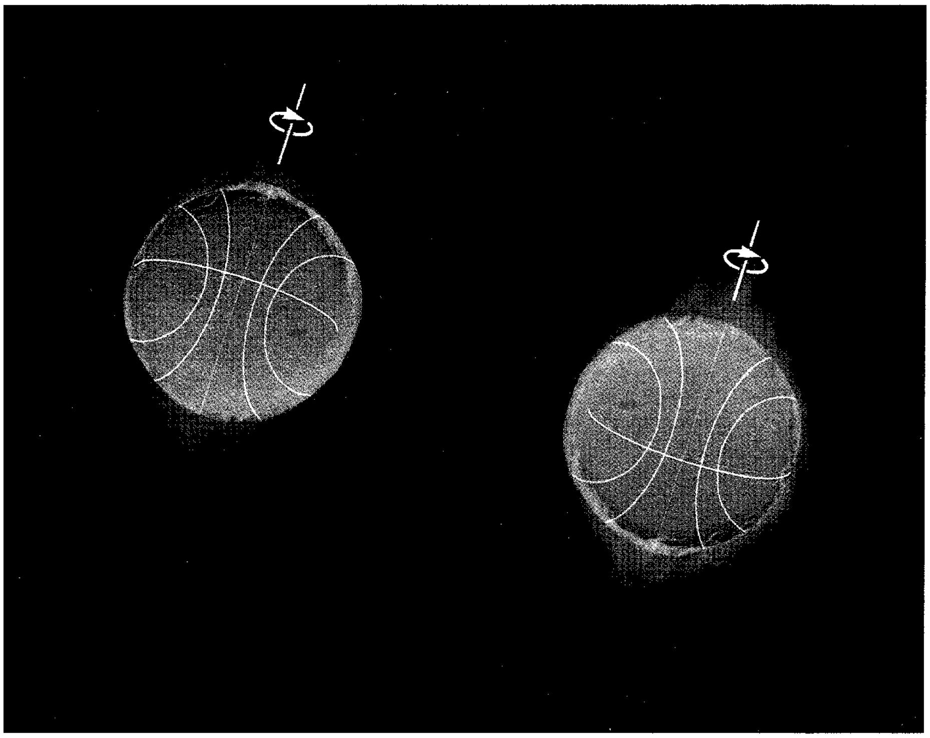
" 'In 1951, at a seminar talk that Minkowski gave in Pasadena on the theories of radio sources, I got mad. I had just published the theory of colliding galaxies in clusters and identified the Cygnus A source with such a pair in collision. Nobody would believe that there were extragalactic radio sources. Minkowski reviewed all the other theories first; and then, at the end of the seminar, as if he were lifting a hideous bug with a pair of pincers, he presented my theory. He said something like: "We all know this situation: people make a theory, and then, astonishingly, they find the evidence for it. Baade and Spitzer invented the collision theory; and now Baade finds the evidence for it in Cygnus A."

" 'I was angry [said Baade] and I said to him "I bet a thousand dollars that Cygnus A is a collision." Minkowski said he could not afford that; he had just bought a house. Then I suggested a case of whiskey, but he would not agree to that either. We finally settled for a bottle, and agreed on the evidence for collision — emission lines of high excitation. I forgot about the thing until, several months later, Minkowski walked into my office and asked "Which brand?" He showed me the spectrum of Cygnus A. It had neon-five [quadruply ionized neon] in emission, and thirty-seven-twenty-seven [ionized oxygen], and many other emission lines. I said to Minkowski: "I would like a bottle of Hudson Bay's Best Procurable," that is the strong stuff the fur hunters drink in Labrador.

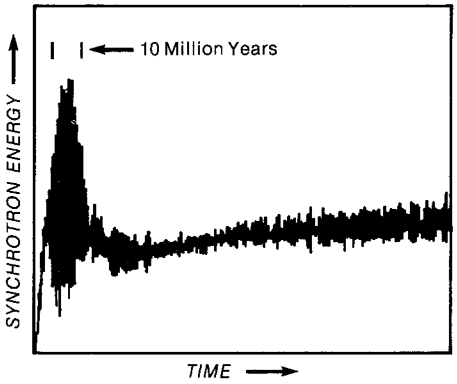
" 'But that was not everything. For me, a bottle is a quart; but what Minkowski brought was a hip flask. I did not drink it. I took the flask home as a trophy. . . . Two days later, it was a Monday, Minkowski visited me in order to show me something — he saw the bottle and emptied it.'

"Baade chuckled: 'Isn't it a shame that you get no returns when the horse you bet on is a dead-sure thing?'

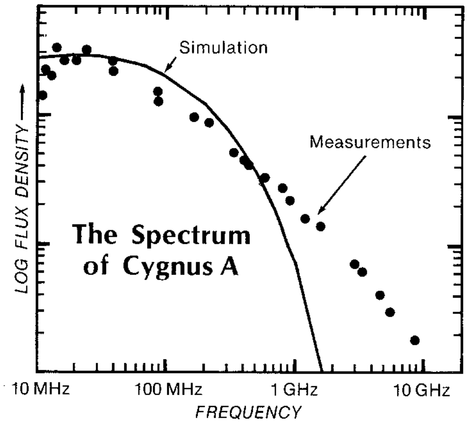
"That was six years ago," the editors noted, "and the horse is dead. Most of the experts would agree now that Minkowski had a right to consume the whiskey



A schematic representation of two rotating, galaxy-size plasma clouds, each containing enough electrons and positive ions to equal the mass of the Milky Way. The author's computer simulations (described on page 22) show that, as these objects interact, they reproduce many features of radio galaxies. Such mimicry is reminiscent of Walter Baade's original concept of galactic collisions. Depicted here are the electric currents in the axial direction (straight orange line along the axis of rotation) and azimuthal direction (slightly curved orange line along the equator), and also the dipolar (yellow) and induced "pinch" (white) magnetic lines of force. The clouds become pinched into more cylindrical shapes along their axes of rotation, but most of the interesting phenomena take place in the



The calculated synchrotron energy radiating from two interacting plasma clouds like those illustrated at left, shown as a function of time.



The observed spectrum of Cygnus A compared to the emission predicted by

because Baade had not won his bet."

This tale should serve as a warning to those who assume that the current explanation of active galaxies is also a sure thing. Although Baade's collisional hypothesis flourished for a brief time, radio observations with higher angular resolution eventually brought about its demise. The most intense radio radiation from Cygnus A, which is produced by the synchrotron mechanism (see box) is not coming from the vicinity of the junction (or, perhaps, dust lane) between the two optical components of the source. Instead, there are *two* regions of radio emission separated by about 1.5 arc minutes, one on each side of the central galaxy or galaxies.

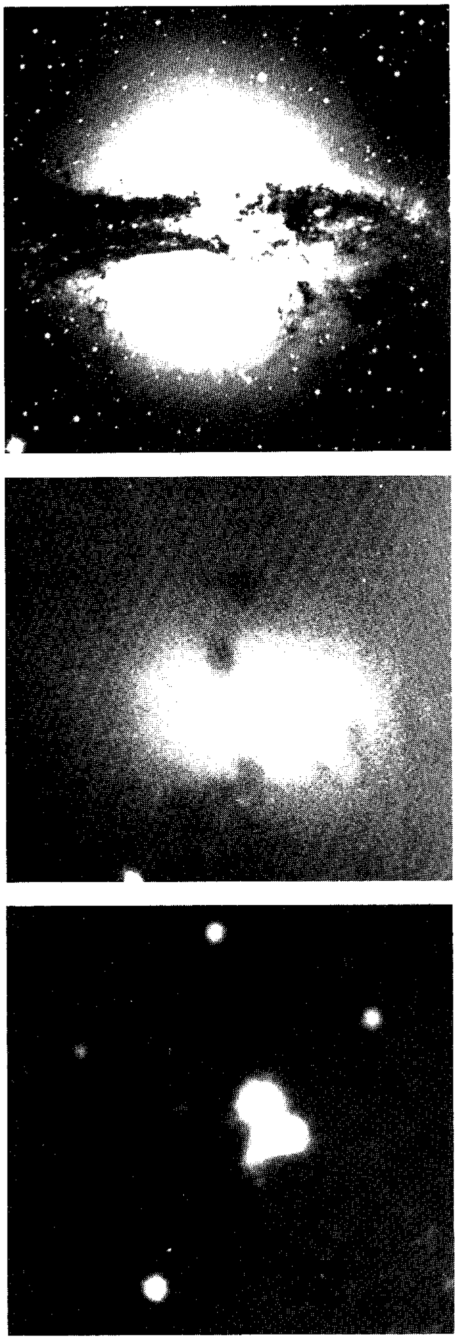
THE PRESENT EXPLANATION

In visual light Cygnus A has a redshift indicating that it is at least 500 million light-years away. To appear as big as it does at this distance, the radio source must be at least 200,000 light-years across, much larger than the visible galaxy. This double radio structure, now known to be common among strong radio sources, plus the seemingly low probability of chance collisions between galaxies, led to the rejection of Baade's hypothesis.

In recent years a new interpretation of double radio sources has emerged, based on the enormous amount of observational data gathered since Baade's time. In this view some sort of spinning "machine" (often dubbed an "engine" or "monster") in a galaxy's nucleus ejects beams of energy in opposite directions along its axis of rotation. This energy can take the form of either a more or less continuous stream of particles or a recurrent ejection of "plasmoids." The latter are clouds of relativistic particles (those moving near the speed of light), magnetic fields, and thermal plasma (a collection of electrons and ions that move about randomly according to the temperature but respond collectively to an electromagnetic field).

Currently, the most popular model of the machine involves a massive black hole that consumes surrounding stars and interstellar matter, and efficiently converts their gravitational potential energy into radiant or kinetic energy, or both, which powers the radio source. The most energy that could possibly be liberated this way corresponds to the rest mass of the infalling matter by Einstein's well-known equation $E = mc^2$, where E is the energy, m is the rest mass of the matter, and c is the speed of light.

Cygnus A emits synchrotron energy in



Three radio galaxies: NGC 5128, associated with the radio source Centaurus A; NGC 1316, associated with Fornax A; and the optical object associated with Cygnus A (3C 405)

SYNCHROTRON RADIATION

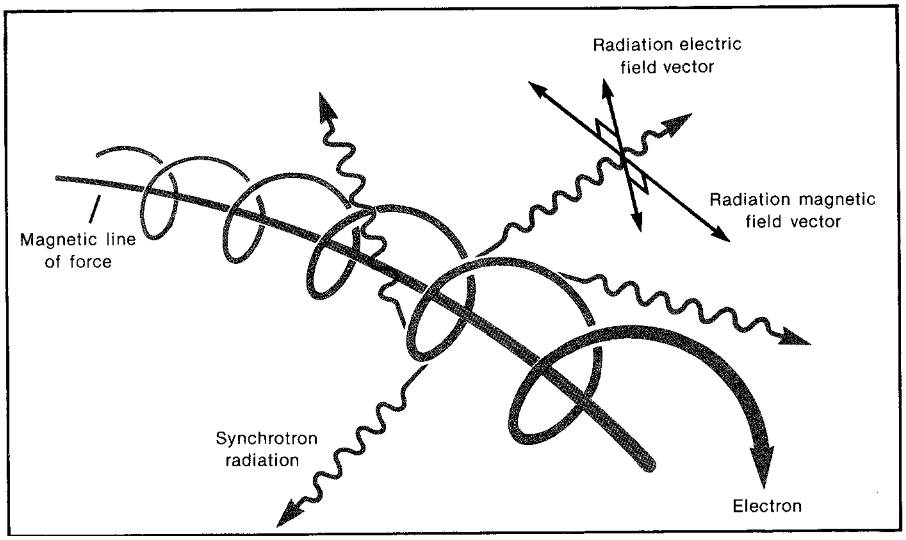
Astronomers have been observing synchrotron radiation for more than two centuries, though unknowingly for most of that time, for it provides most of the Crab nebula's visible light. The name comes from the fact that this emission was first seen for what it was in particle accelerators called synchrotrons. It is emitted whenever an electron moving near the speed of light meets a magnetic field (or component of a field) that lies at an angle to its path, as shown in the accompanying illustration.

Synchrotron radiation has a continuous spectrum, its power being smoothly distributed over a wide range of wavelengths in such a way that its intensity generally increases toward longer wavelengths. The radiation is emitted in a narrow beam along the direction of the electron's motion, with the predominant wavelength given off by an individual particle depending on its velocity and the strength of the magnetic field in which it is moving.

An important characteristic of synchrotron radiation is that it is linearly polarized. In fact, the discovery of strong polarization in the continuous light of the Crab nebula led directly to the realization that the synchrotron mechanism produces the light.

Synchrotron radiation from an astronomical source contains contributions from many electrons moving with different velocities. Analysis of this emission yields the electrons' energy distribution, which can then be used as a known quantity in computer simulations of particle behavior.

The occurrence of this radiation mechanism shows that high-energy charged particles and extensive magnetic fields are common and important in astronomical objects, and that enormous amounts of energy may be stored in the form of these two ingredients.



cess of 20 billion times the total power itput of the Sun, or some 10^{44} ergs per cond. Furthermore, it is estimated that e lifetime of such a source may be about) million years. Over this period the engy emitted in the form of radio waves one is enormous — some 100,000 times e amount that would be produced if the itire mass of the Sun were converted into iergy. Since a typical energy conversion ocess might have an efficiency of one ercent, some 10 million solar masses of uel" might be needed — a fraction of a lar mass a year.

Short-wavelength radio observations prode evidence of rapid activity in the nuclei radio sources. In several instances the iriability points to sizes between a few ;ht-months and a few light-years for the nitting regions. The gravitational bindg energy for a galactic nucleus of such a nall size would be somewhere around 10^{60} gs. This value may be high enough to oduce the observed synchrotron energy if conversion efficiency of 10 percent or ore can be achieved.

Thus, the black-hole hypothesis can ausibly account for a radio source's progious energy output. Unfortunately, this not a precise model that can be comired directly with observation. Furtherore, no serious proposals have been put irward to explain the observed comlexities of such sources with a relativesmall number of adjustable parameters. or these and other reasons, many serational astronomers and other scientists main skeptical of the concept of massive lack holes, despite claims that data from idio sources demand it.

Part of this skepticism is due to the ngular nature of a black hole. However, iis argument is not decisive. If black oles do exist, they are unique and beyond ir previous experience; the conventional iles of physics may not apply. Still, must e throw out basic physical laws such as ie conservation of matter and energy? uch drastic steps ought not to be taken efore other possibilities are ruled out.

ALTERNATIVES

Can conventional, non-black-hole physs account for the enormous amounts of idiation from powerful extragalactic obcts such as double radio sources? Morever, can a conventional mechanism reprouce observed details, such as the radiaon's intensity at different frequencies and s distribution in space? Any explanation ould inspire more confidence if it could xplain how the asymmetric jets that are ften observed could power symmetric raio lobes, why "hot spots" are seen in ›bes, and why those spots often can be ned up with the galaxy's nucleus over normous distances.

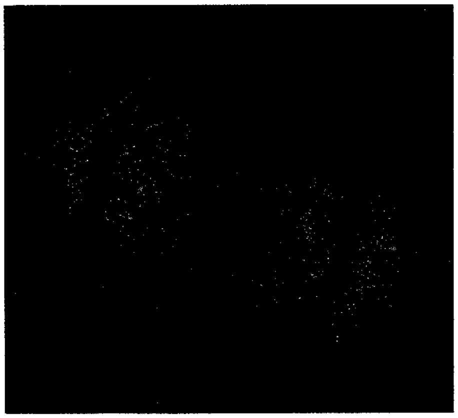
Only two ingredients are needed to prouce synchrotron radiation: fast-moving

that these two entities interact on a galactic scale was first advanced by the Swedish physicist Hannes Alfvén nearly 50 years ago. Since then magnetic fields have been used relatively little in astrophysics, though their importance, in the formation of stars for example, is well appreciated. The reason is quite simple: The interaction of complex magnetic fields and matter distributions is a mathematical nightmare. Fortunately, a remedy for this problem is now at hand.

GRINDING OUT THE NUMBERS

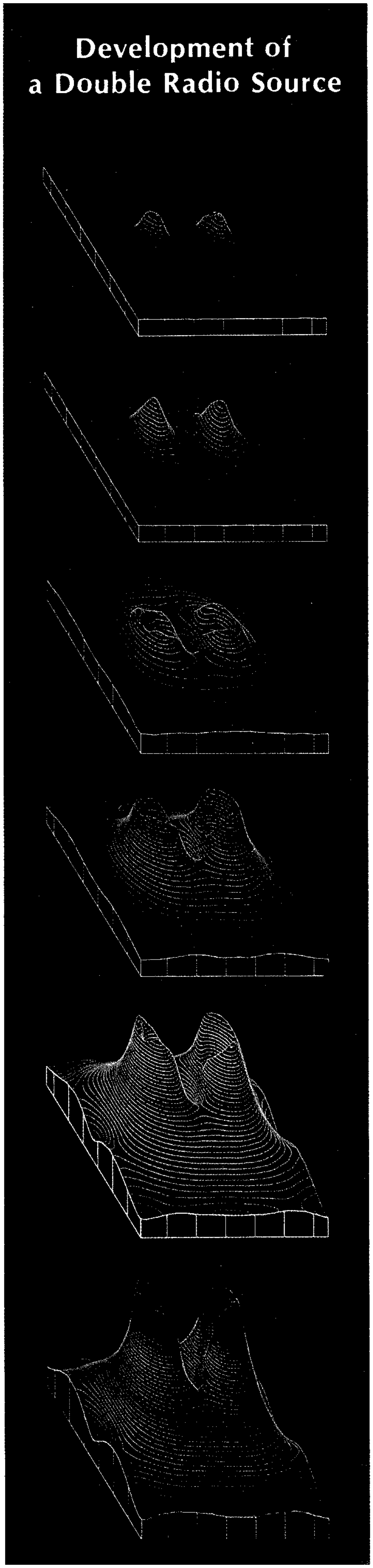
The continued growth of large computing systems has, in the last few years, led to a threshold. It is now possible to follow, by numerical calculation, the simultaneous motions of millions of charged particles in three dimensions under the influence of electromagnetic fields. Very fast machines with enormous memory capacity are needed. Each time step in the motion of the electrons and ions might require the calculation of, say, 500,000 individual electric-field, magnetic-field, and electric-current components, in addition to updating the position and velocity of every individual particle.

The national laboratories at Los Alamos and Livermore each have five Cray supercomputers linked together at their respective sites. Each one of the Cray machines can perform 20 to 60 million calculations per second and has a memory of up to four million words. This computational resource opens up unprecedented opportunities for studying such astrophysical phenomena as auroras, planetary magnetospheres, the solar atmosphere, and, not



At an early stage in the author's computer simulation, interacting plasma clouds produce two regions emitting very intense synchrotron radiation. This diagram shows how a radio image of such a region might appear.

Right: **Development of the magnetic-field structure as the two clouds interact. The base is the plane of the sky; greater height above the base and bluer color indicate stronger fields. Note the arcs of strong field that develop around the central magnetic "sump." Time**



Development of a Double Radio Source

least, radio-emitting clouds of galactic dimensions.

A rotating plasma cloud in a magnetic field generates a direct electric current. In fact, this mechanism is thought to power auroras on Earth (see page 534 of the December, 1982, issue). J. C. Green and I have carried out computer simulations to see what happens when a rotating, galaxy-size cloud of 100 billion solar masses (about the mass of the Milky Way) contains a dipole magnetic field (like that of a bar magnet) aligned with the cloud's rotation axis. We found that an electric field is formed, and this in turn produces direct current flow. Its path can be represented by axial and azimuthal components, seen in the highly schematic diagram of plasma clouds on page 19. This picture sets the stage for the interesting results that follow when two such clouds interact.

Two neighboring clouds will attract each other magnetically if they are aligned as shown in that illustration. As they approach, the repulsive forces due to the counterflowing azimuthal currents produce a braking effect on electrons spiraling around the magnetic field lines. This acceleration produces a burst of synchrotron radiation lasting some 10 million years, as shown in the graph on page 19. The average power radiated during the burst is about the same as that observed from Cygnus A. The radio spectrum of Cygnus A is also shown and is compared to the energy spectrum computed to result from the clouds in our simulation. The correspondence is noteworthy though not perfect.

What about the frequently observed opposed ejection of plasmoids or beams? Our simulations show a way in which similar features can be produced without the need for a black hole. As the clouds approach, the electric fields are nearly constant, while the currents and magnetic fields increase. The magnetic field lines move outward, leaving a hole or "magnetic sump" at the center into which intercloud plasma flows. The sump formation (and subsequent outward particle acceleration) is due to the reconnection of magnetic field lines and magnetic pumping, phenomena that vary much more rapidly than the time-scale at which the clouds approach.

Early in the process the masses of particles collide but, due to their magnetic fields, do not coalesce readily. Instead, a very energetic interaction region is formed between them where the plasma is compressed, an important factor for the formation of stars, X-rays, and the emission lines that caused Minkowski's concession to Baade.

Later in the evolution of the interacting clouds, the magnetic-field lines squeeze the centrally accumulated matter harder and harder. Plasmoids are formed and forced outward; time-lapse movies of our simulations show them ramming repeatedly against the cusp-shaped field lines. Eventually, magnetic pressure squeezes the plasmoids into two well-defined and oppositely directed "beams," with the magnetic field directed along them. The similarity of these beams to observed radio jets is quite interesting.

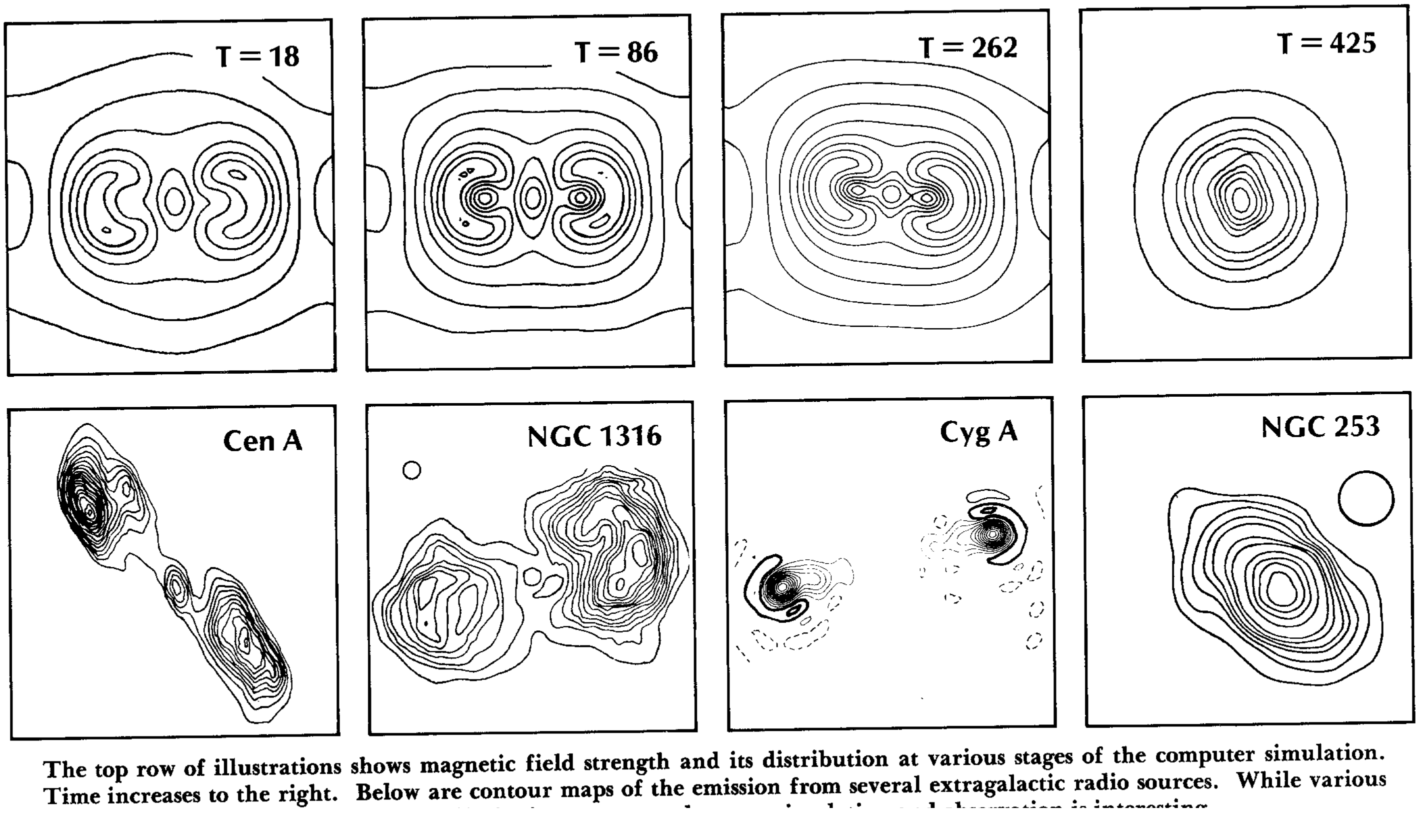
All the phenomena that appear in our simulations, such as central sources, oppositely directed hot spots, cusps, and jets, are just the products of an interacting, magnetized plasma. In particular, the central sump may contain only charged particles and magnetic fields; no black hole is present or needed. The energy for the synchrotron radiation comes from the rotational energy of the interacting clouds.

Do such clouds exist? Perhaps not. Yet the assumption that they do, which does not demand the overthrow of any well-established physical laws, seems no more adventuresome (though perhaps less exciting) than the assumption that massive black holes exist. It is also subject to more detailed investigation by improved simulations in the future.

The interpretation of complex and unusual observational results depends on what an investigator has seen in the past, on the ingenuity exercised in noting significant differences and similarities, and on the available equipment, both physical and theoretical. Baade's interpretation of Cygnus A seemed correct at first; later it lost favor. Will studies made possible by the availability of large computer systems bring it back to popularity once more?

REFERENCES

A detailed account of the results summarized here will appear in a paper by J. C. Green and myself in *Astrophysics and Space Science*. The properties of magnetized galactic plasma are described by H. Alfvén in *Cosmic Plasma* (D. Reidel, 1981), while a recent survey of double radio sources by G. C. Perola is in the journal *Fundamentals of Cosmic Physics*, *7*, 59, 1981. SPLASH, the three-dimensional electromagnetic particle code, is reviewed by O. Buneman, C. W. Barnes, J. C. Green, and D. E. Nielsen in the *Journal of Computational Physics*, *38*, 1, 1980.



The top row of illustrations shows magnetic field strength and its distribution at various stages of the computer simulation. Time increases to the right. Below are contour maps of the emission from several extragalactic radio sources. While various