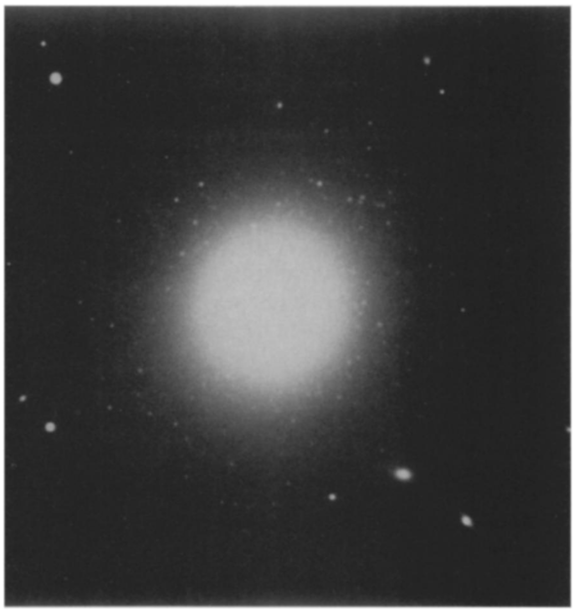
GALAXIES THAT CAME IN FROM THE COLD

In a universe of 90 percent cold matter, hot, bright galaxies can still form



Photos: Natl. Optical Astro. Obs.

M87, giant elliptical galaxy in Virgo.

An S0 galaxy, NGC 3718 in Ursa Major.

By DIETRICK E. THOMSEN

Astronomers, the people whose job it is to watch the rest of the universe, have mostly convinced themselves that they are able to watch only a very small part of it. Most of it, they say, consists of "dark" matter, matter that gives off no radiation that we observe. This conviction comes originally from studies of the clustering of galaxies, a typical phenomenon. The only known force that can hold such clusters together is gravity, but for the gravitational forces to be strong enough, the clusters must contain an overwhelming majority of dark matter, up to nine times as much as the matter we see. The idea of a large amount of dark matter also fits in with the program of those cosmologists who believe the universe to be closed. Again, for gravity to be strong enough to stop and reverse the expansion of the universe, ultimately causing a recollapse — which is how a closed universe would behave — large amounts of dark matter must exist.

Given these important reasons for believing in dark matter, the question arises whether other things in the universe can be as we see them in the light — or perhaps the dark — of such a belief. For example, could galaxies in the presence of so much dark matter have evolved to the shapes, associations and dynamical properties that astronomers find them to have?

A group of astronomers and physicists working mostly in Santa Cruz, Calif., has made a theoretical study showing that such an evolution of galaxies is possible, if one assumes that the dark matter was cold at the start. One of the astronomers involved in the study, Sandra Faber of the University of California at Santa Cruz, says the result of the study "gives us a reasonable way of understanding the morphology of galaxies and why that morphology is tied to a galaxy's environment — and in this picture that tie is more complicated than people have imagined before."

In speculating about the nature of dark matter, cosmologists have usually assumed that it consists of one or another variety of subatomic particle scattered around the universe in almost unimaginably huge numbers. Cosmologists first considered hot dark matter, dark matter that shared the ambient temperature of the universe. Neutrinos were a favorite choice for hot dark matter. But many cosmologists now argue that hot dark matter doesn't fit; the dark matter has to be cold — that is, able to maintain a lower temperature than the rest of the universe. Cold dark matter has to be fairly exotic: magnetic monopoles, axions or gravitons, none of which has ever been found by experimenters, although theorists believe they exist (SN: 6/23/84, p. 396).

This group of investigators, which includes Faber, George Blumenthal and Joel R. Primack of the University of California at Santa Cruz and Ricardo Flores of Brandeis University in Waltham, Mass., started with the assumption that the universe is 90 percent cold dark matter. They did not choose a particular particle. The only restriction on the identity of the dark matter is that it is nonbaryonic. In this context, that means mainly that the matter is not composed of neutrons or protons; it has to be some particle that does not take part in the structure of ordinary atoms and molecules. The dark matter is also assumed to be dissipationless — that is, it does not lose energy by rubbing together and producing heat.

To this assumption of cold, nonbaryonic, dissipationless dark matter, Blumenthal says, they added only one other assumption: Galaxies form by condensing around density fluctuations, small regions where the density of matter is higher than the average density, in an otherwise featureless primeval universe that consists of matter spread more or less evenly throughout space. And these fluctuations have a particular spectrum of densities proposed by the Russian physicist Yakov Borisovich Zeldovich.

With these two assumptions the group set up a calculation called an N-body simulation. In this the universe begins as N (an extremely large number) of small bodies, 10 percent baryonic, 90 percent not, and gravity is turned on. The calculation describes what happens as time passes. Such a computation is done on a fairly large and fast computer. It would be extremely impractical, if not impossible, by hand. The question is whether it will come up with the characteristics of galaxies as they are in fact observed.

Galaxies must first condense around the density fluctuations *à la* Zeldovich, and they must condense in a certain way. The baryonic matter, which produces the light and other radiations we observe, must go to the center of each galaxy, leaving outside of itself a sizable halo composed almost entirely of the dark matter.

Galaxies rotate, but not rigidly. The rotation speed of their different parts varies according to distance from the galaxy's center. The "rotation curves" that chart this variation depend on the distribution of matter throughout the galaxy, including the unseen halos. Mass distributions that justify the observed rotation curves must come out of the N-body simulation.

Galaxies come in different shapes that fall into three main categories: elliptical, spiral and S0, which has characteristics of the other two. S0 galaxies do not have prominently visible spiral arms, but they do have the wedge-shaped dark areas that spirals have between their arms. Ellipticals and spirals tend to appear in different neighborhoods. The N-body simulation must somehow come up with these associations.

According to its authors, this N-body simulation satisfies those criteria. Blumenthal points out that the N-body simulation "allowed us to make a prediction of the mass range of galaxies." Galaxies need to cool as they form, and in this picture the baryons are responsible for the cooling. A diagram to plot baryon density vs. temperature, says Blumenthal, would be divided into two regions: one in which the cooling time is greater than the free-fall time (that is, the time it takes gravity to collapse the mass into a galaxy), the other in which the free-fall time is greater than the cooling time. Condensed objects, such as galaxies, ought to fall in the part of the diagram where the cooling time is short compared to the free-fall time. In fact, a plot of observed densities and temperatures of galaxies shows them all in the correct portion of the diagram.

On the other hand, *clusters* of galaxies — which on this scale are uncondensed objects — fall in the opposite portion of the diagram. From the permitted range for galaxies one can calculate the range of masses of galaxies. The range runs from 100 million to 1 trillion times the mass of the sun. This, says Blumenthal, is just what is observed. "This is one of the first times anybody has come up with this," he says. Most other attempts to predict the masses of galaxies from theoretical principles have been inaccurate.

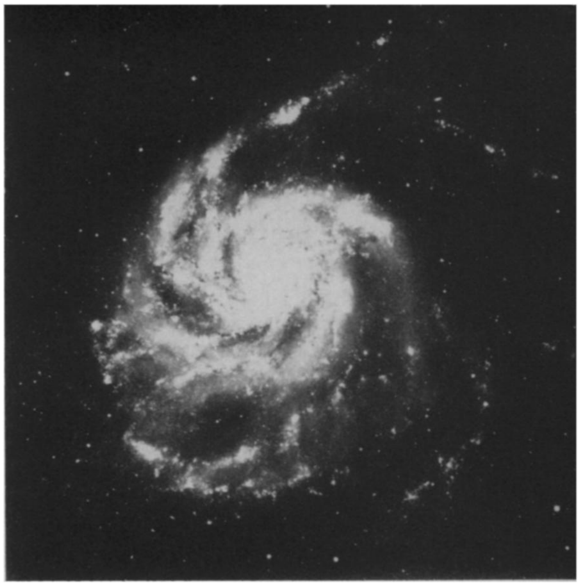
Instead of density, one might consider mass and temperature. On a graph representing these data, one can plot the density fluctuations of the primeval universe, around which galaxies are supposed to have formed: One can draw lines on this diagram corresponding to fluctuations of different sizes — one standard deviation, two standard deviations, etc. One then finds that different morphological types of galaxies run along different lines, giving a relation between the size of the primordial fluctuation and the shape of the resulting galaxy, Blumenthal says. It also fits in a statistical sense, in that the larger the fluctuation, the fewer there are.

Galaxy rotation and how it got started is one of the great mysteries of astrophysics. In a Big Bang universe, linear motions are easy to explain: They result from the bang. But what started rotary motions? To convert linear motions to rotary ones usually takes some trickery, so that at least one astrophysicist has suggested that the universe as a whole rotates and so transmits some of its rotation to objects within it.

In this model of galaxy condensation, the difference between the dissipationless 90 percent and the dissipational baryonic 10 percent makes the baryons cluster around the core of the galaxy inside a large dark halo. The various collisions involved in cooling the baryons can give them a bit of rotary motion. As the whole galaxy condenses to about one-tenth its original size, the baryons spin up, and the whole galaxy winds up going around. Furthermore, the relation between the distance of a given part of the galaxy from its center and the speed of that part's rotation comes out as observed.

An aspect they're still working on, according to Blumenthal, is how a galaxy's environment affects its evolution and morphology. Already, says Faber, the group has a quantitative picture to relate all manner of galactic properties to what might be found nearby.

Some time ago Allan Dressler of Carnegie-Mellon University in Pittsburgh found a relation between a galaxy's morphology and the density of galaxies in the neighborhood. If the density of galaxies in a particular region of space is low, spirals are likely to be the majority. Where the local density of galaxies is high, ellipticals tend to predominate. By adding the assumption that elliptical galaxies tend more than spirals to come from higher-amplitude primeval density fluctuations, the N-body simulation will yield results similar to Dressler's, although, says Blumenthal, "at higher densities we tend to predict more ellipticals and fewer S0s than are observed." Nevertheless, he continues, "purely from the spectrum of fluctuations, we can calculate the relation between the density of galaxies on a large scale and the amplitude of fluctuations of the galactic scale."


A typical spiral galaxy, NGC 5457.


Galaxy cluster in Virgo includes M84, M86.

Among the number of detailed questions still to be resolved is one very large one: the large-scale structure of the universe. Taking the assumptions of this theory to the scale of superclusters and other very large structures, says Faber, would lead to the conclusion that the same spectrum found on a galactic scale extends to larger scales, suggesting that on a large scale the universe is smooth.

That is not the way things are observed. More and more, astronomers are finding that the universe on the largest scales consists of long, stringy superclusters of galaxies separated by large voids. And so Faber asks: "Is matter that lumpily distributed, or is there something about galaxy formation that causes it to be patchy so that we're only illuminating part of it?" ☐