A Closed Universe May Be Axionomatic

In their search for dark matter to close the universe, cosmologists are switching their tune from 'hot time' to 'cold, cold heart'

By DIETRICK E. THOMSEN

"The sun never sets on the Spanish Empire." So boasted the Spanish ambassador in the court of King Henri IV of France. To which the king replied: "That's because God won't trust a Spaniard in the dark." It seems God won't trust a neutrino in the dark, either. Neutrinos used to be a prime candidate for the dark, unseen matter that is supposed to pervade the universe and decisively affect its shape and ultimate fate. But now, neutrinos won't do, that is if you believe what one observer calls the Santa Barbara-Berkeley school — "They seem to be taking over without opposition," he says. Something more exotic — axions, gravitinos, photinos, magnetic monopoles — is more likely.

Two reasons are usually adduced for the presence of large amounts of dark matter in the universe. The first has to do with the internal dynamics of galaxies, as pointed out by Jay S. Gallagher of Kitt Peak National Observatory in Tucson, Ariz. Addressing the recent Inner Space/Outer Space meeting held in Fermilab in Batavia, Ill., he related that studies of the rotation of galaxies and the motions of individual stars in them that were done in the early 1970s indicate that generally there must be unseen matter in them and it must extend beyond the discs of stars that we see. This is usually called the "missing mass problem," but, as Gallagher says, it would better be called the "missing light problem." There is a lot of something there that doesn't glow.

The second reason for dark matter is a philosophical or aesthetic one, as presented by Simon White of the University of California at Santa Barbara. He says most cosmologists would like to believe that the universe is "marginally closed." The conditions that determine whether the universe is open and will expand forever or whether it is closed and will eventually stop expanding and recollapse were established very early in history. It seems highly unlikely (and very anthropocentric), White says, that these conditions should be such that just when we are here to see it, the universe is on the point of taking off into rapid endless expansion. A closed universe gives more options and more of a random choice for initial conditions to lead to our present state.

So for philosophical reasons White and others would like the universe to be marginally closed — slightly curved back on itself. (If it were strongly closed, sharply curved back on itself, we would know it, or we would never have arisen to see it.) This condition also requires more matter than we see. Whether they start from the angle of galactic dynamics or from that of cosmic philosophy, astrophysicists also tend to assume, as Gallagher puts it, that the galaxies trace out the mass distribution. That is, the dark matter associates with the shining matter in galaxies and clusters of galaxies. Suggestions as to what it is take off from there.

At first astrophysicists suggested the obvious, baryonic matter, that is, matter made of neutrons and protons like the ordinary stuff we handle all the time. For some reason it wouldn't be hot enough to glow. That doesn't work, however. White says the presence of so much unseen baryonic matter would have altered the course of nucleosynthesis, the production of heavier elements out of lighter ones. We would not see the abundances, particularly of helium, that we do see. The dark matter has to be nonbaryonic.

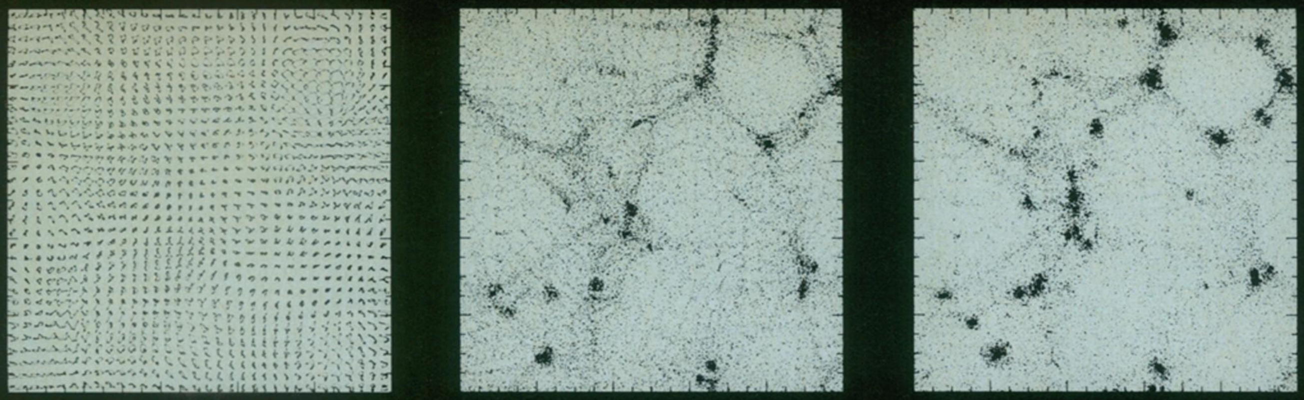
Some like it hot; some like it cold. (No votes for pease porridge, that's baryonic.) The obvious hot choice was neutrinos. As White says, they're attractive because we already know they exist; the other choices are much more speculative. When the existence of neutrinos was first theorized, they were supposed to have no rest mass. That would render them unfit for this duty, as without mass they could not exert the gravitational forces required to do what they have to in the dynamics of galaxies or in the closure of the universe. However, more modern theories allow neutrinos to have a very small mass, and there is a Russian experiment — so far neither confirmed nor contradicted — that shows them to have about 30 electron-volts each.

That's not much mass per neutrino, but colossal numbers of neutrinos taken collectively could still do the job. They could have been produced in such numbers at the beginning of the universe and stuck around in such numbers, as they interact almost not at all with other matter. This prevents them from being destroyed.

White and colleagues did a computer simulation to discover whether they would work. This involved simulating part of the universe, a large cube, distributing 32,768 particles in it and letting them evolve under selfgravitation and the proper dynamical equations (Newton's and Poisson's) as neutrinos would. The idea is to see whether they reproduce the distribution of galaxies as observed.

As the provinces of the Spanish Empire were distributed around the earth at the time the ambassador made his boast, so the galaxies are distributed around the universe, and like the distribution of Spanish provinces that of the galaxies is not even. It is a particular map that has to be reproduced. White told the Inner Space/Outer Space meeting that the evolution of the neutrino-dominated model just doesn't cut it. Among other things it leads to values for the Hubble constant (the measure of the rate of expansion of the universe) outside the range acceptable from other observations, and it leads to massive clusters of neutrinos that should be giving off X-rays we don't happen to see. "The neutrino distribution looks unlike the galactic distribution, and it's highly unlikely you could hide the fact," he says.

So it's back to the drawing board and a consideration of cold matter: axions, gravitinos, photinos, maybe magnetic monopoles. These things are called cold because they do not follow the customary thermodynamics. Neutrinos, baryons, the photons of electromagnetic radiation, all partake of the ambient temperature of the universe. Their temperature, which de-



Simulation carried out at the Univ. of Calif., Berkeley, by Simon White, Carlos Frenk & Marc Davis

To simulate a neutrino-dominated universe, a large hypothetical cube is filled with a distribution of particles, and the computer calculates how their positions will change as the universe evolves. Gradually they clump, but the clumping does not match the distribution of galaxies.

pends on their velocity, is a measure of the amount of agitation in the aggregate, how violently things seem to be rushing around. Cold matter does not follow this relationship. Its temperature does not depend on velocity, and collectively these cold particles can maintain temperatures well below the universal ambience. This gives them some advantages as candidates for the dark matter.

White stresses that the cold matter could be any of the suggested particles, axions, photinos, gravitinos, monopoles. Axions, however, are particular favorites of some other people. Axions are predicted by the grand unified theories (GUTS), which are trying to unite all of known particle physics into a single theoretical framework. As such, they might be called one step beyond currently accepted particle physics. (Monopoles come from GUTS too, but they have serious problems peculiar to themselves.) Photinos and gravitinos are predictions of the supersymmetry theories that try to unite particle physics with gravitation phenomena. They are at least two steps beyond, and some physicists would place them definitely in the twilight zone.

Axions are particles closely related to geometric effects. According to Pierre Sikivie of the University of Florida in Gainesville, they are not ordinary particles but belong to the class called pseudo-Goldstone bosons. It has been rather widely popularized that modern physics makes a close connection between forces and geometry; most people have heard that gravitational forces are determined by the curvature of spacetime. What may not be so widely popularized is that modern physics also makes a close connection between geometry and matter. The properties and existence of certain particles can depend on geometric considerations. Axions are such.

Axions exist because the behavior of quarks (the building blocks of neutrons, protons and related particles) obeys certain spatial symmetries. Nature generally respects a symmetry between left-handedness and right-handedness and between positive and negative electric charge. Usually these two kinds of opposites balance. A few particle processes violate these symmetries, producing, for example, more left-handed particles than right-handed ones. The behavior of quarks could conceivably have violated these symmetries, but it is not seen to do so. Axions exist because the violation does not occur.

If the behavior of quarks violated the left-right and charge symmetries, a certain angle would appear between two directions that arise in the geometric analysis of quark dynamics. That angle would measure the amount of the deviation. As no deviation is observed, that angle has to be zero. Axions are the measure of what that angle might have been. According to the logic of the theory, Nature, in choosing to make that angle zero, necessarily also made axions and gave them qualities representing what that angle could have been. (Or at least she did if the theory is correct.) Axions are thus both a measure of the deviation that might have been and a guarantee that it doesn't exist.

Axions have a very small mass, about a hundred-thousandth of an electron's, Sikivie says, but their numbers are huge enough to do the gravitational job.

Sikivie stresses a couple of advantages for axions as candidates for the dark matter. First, they are cold. Their temperature depends not on velocity but on another geometric consideration, the horizon length of the universe. The horizon length is the distance over which communication is effective, the portion of the universe in which things can communicate with each other. At our epoch, the horizon length is 10 billion light-years or more. At the epoch when these clusterings were beginning, Sikivie says, the horizon length was on the order of 60 kilometers. That permitted the axions to maintain a temperature among themselves of about 3 kelvins when the rest of the universe was at billions of kelvins. That would make it easier to concentrate them into the haloes of galaxies than the hot and fast-moving neutrinos.

Axions' second advantage is quantum mechanical. Axions are bosons, subject to Bose-Einstein statistical laws. Neutrinos are fermions, subject to Fermi-Dirac statistics. There is a limit to how many fermions can be jammed together in one place, but there's no limit to the number of bosons.

A number of experiments have looked for axions, but not yet found any. Sikivie proposes another. A magnetic field can make an axion change into a photon, which might be light or X-rays, and which physicists know how to detect. Sikivie proposes setting up a large box, 17 by 50 by 150 centimeters coated with silver. The box would be pervaded by a very strong magnetic field, 8 teslas. An axion entering this chamber would be converted into an X-ray photon by the geometric condition known as a magnetic field, and that photon, Sikivie contends, should be detectable.

With advantages for axions in particular and cold matter in general, White ran computer simulations in which cold matter was represented. They come out better than the neutrino ones, but there are still problems. To get the cold matter to follow the distribution of the galaxies, one is driven to an overall density that predicts an open universe. This, as White contends, is philosophically undesirable. So he raises the question whether the dark matter necessarily has to follow the distribution of galaxies. That question is also being raised by people who study the distribution of galaxies, and who find serious deviations, not just slight ones, from random and homogeneous distribution. The dark matter represents the overwhelming majority of the universe's mass (if the universe *is* marginally closed). Why should it necessarily follow the distribution of the small portion that glows in the dark? □