Soviet Work Suggests Mixmaster Singularity at Origin

If Einstein's general relativity is right, one can say that the universe started from a singularity, possibly infinite density. So say Isaac M. Khalatnikov and Evgeny M. Lifshitz (*Phys. Rev. Lett.* **24**, 76, 1970), who recently showed that one can construct a general solution of the Einstein equations with a "Mixmaster" singularity; the result suggests that the beginning and end of the universe or the final state of a collapsing star has a singularity near which the object of interest contracts (or expands) while at the same time it is alternately squeezed into the shape of a pancake, then a cigar, then a pancake and so on.

Khalatnikov is perhaps best known for his work in superfluidity and his collaboration with Lev Davidovitch Landau. Khalatnikov is director of the Landau Institute for Theoretical Physics, a center for solid-state theory established a few years ago at Chernegelovga, 55 kilometers northeast of Moscow.

He was in the US to attend a Soviet–American meeting on solid-state theory at Rockefeller University, but he was eager to talk to us about his work in cosmology.

Physical singularities? For many years cosmologists have argued over whether or not the final or initial states of the universe are truly physically singular. Although a "big-bang" origin was always implicit in the Einstein equations, Einstein himself at first disliked the conclusion and modified his equations with a cosmological constant. With the discovery of red shifts, Einstein accepted the big bang. Proponents of the steady-state theory, such as Fred Hoyle and J. V. Narlikar, had to introduce concepts like a "C" field, which allows new matter to be created to fill up the empty spaces left when old matter spreads out. With the discovery of the 3-K background radiation, the case for the big bang looked unbeatable.

Ten years ago Khalatnikov and Lifshitz (both then at the Institute for Physical Problems in Moscow) began studying the singularity problem. At first their work tended to show that the Einstein equations do not have genuine singularities, that the infinities found were due to the simplifications introduced. Five years ago Khalatnikov's student, Vladimir Belinski, joined the effort, after Lifshitz became deeply involved in writing his famous course of theoretical physics. (Landau was no longer able to collaborate.)

In the middle and late 1960's a number of theorems were developed by Roger Penrose, Steven Hawking and Robert Geroch, which showed that under fairly general circumstances some type of singularity does arise, that some kind of big bang occurred, but its exact nature was not known.

Meanwhile the Russian work was proceeding. Khalatnikov explained to us that although they could not find a general solution for ten nonlinear partial differential equations of second order, it was possible for them to investigate the form of the solution near a singular point (assuming there was such a point). They found a solution for a nonhomogeneous universe with seven arbitrary functions of space coordinates. (A general solution requires eight.) It has such properties as infinite density of matter near the singularity, either at the origin or at the end of the universe.

Khalatnikov explained that the seven-functional solution is not general and not stable; one can find some dangerous perturbations that will destroy this solution. They then perturbed the seven-functional solution to study its evolution, to see whether one approaches a regular point (finite density) or one reaches the eight-functional singular solution.

Mixmaster. They found[1] under their very general assumptions that one approaches a singularity, which has many of the properties of the Mixmaster singularity studied by Charles Misner[2] (of the University of Maryland) for a very simple model. This simple model was also independently investigated by Khalatnikov and Lifshitz. It is one of the nine simple, homogeneous models of the universe corresponding to nine types of homogeneity delineated by Bianchi around 1900; it is the so-called "Bianchi type IX" model, and it contains all the dangerous perturbations throughout all time.

Misner studied the homogeneous universe, for which everything is es-

KHALATNIKOV says that the universe must have started with a "Mixmaster" singularity. He is director of a new institute with many outstanding solid-state theorists.

sentially independent of space, only dependent on time. The Russian work started with the same model and then investigated the more general case in which one assumes from the beginning an arbitrary dependence on space and time; it essentially proves that spatial variations are irrelevant and that you get the same qualitative behavior as in Misner's special case.

Just what is a Mixmaster singularity? Two types of motions are superimposed on each other, one a general overall contraction towards the singularity, in which the density rises smoothly and more and more rapidly as time goes on; another is an oscillatory motion, in which matter is alternately squeezed in one direction and then the other, like a Mixmaster or a taffy-pulling machine. So while the overall compression continues, matter is alternately squeezed into a pancake in one epoch, a cigar in another epoch, a pancake, etc, and the process gets more and more rapid. Although there are an infinite number of squeezes, an observer's clock (provided it could withstand the procedure) would measure the elapsed time as finite. The Khalatnikov–Lifshitz–Belinski singularity will have roughly the same local behavior as the mixmaster singularity, but because it is for nonhomogeneous space the behavior from point to point in the space will change. At any instant of time the axes of elongation will point in a different direction in different regions of space. Furthermore the axis of the pancake or the cigar will rotate with time.

In KLB-type universes, Khalatnikov explained, it is more natural to use the logarithm of the proper time. "We have some finite interval of the time, but the whole age of the universe is from zero to infinity. But if we take the logarithm of time the evolution is from minus infinity to infinity. Then the singularity is at minus infinity and this process of changing of epochs will be infinite.

"The origin of the universe must have produced a lot of gravitational waves at the beginning, and therefore there must be a dense flux of isotropic gravitational waves. It's possible that the main part of the energy of our universe is in the form of continuous gravitational waves. But I don't know how to detect them, this whole continuous spectrum of gravitational waves." Joseph Weber (University of Maryland) detects pulses of gravitational waves, in which the energy is concentrated in small regions of space and time. Continuous gravitational radiation (arising from the origin of the universe) would be spread so thinly throughout space that it would be below the level of detectability.

Anisotropy or isotropy. Misner aims to explain the fantastic uniformity of the 3-K blackbody radiation, which has been observed to be isotropic to within a fraction of one percent. In the classical Friedman–Robertson–Walker model different parts of the universe remain totally isolated from each other and have no way of influencing each other until very late in time; so objects more than 30 deg apart in the sky would never have known of each other's existence, Misner told us. "I dug out the possibility that in the initial singularity, in the first very short period of time (perhaps much less than a second), they could interact with each other and come into agreement as to what their properties should be. Even though they'd never talk to each other later, by following the same laws of physics, they'd end up at the same temperature when they emitted the blackbody radiation. This possibility of communication exists only in the more exotic types of singularity, which I've called the Mixmaster, and is absolutely forbidden in the traditional types of singularities in the perfectly symmetric Friedman–Robertson–Walker universe."

KHALATNIKOV

Khalatnikov explained that the universe could be nonisotropic and oscillatory at the beginning because near the singularity the influence of matter

is negligible. "The influence of matter starts at a later stage when the universe expands a little. At the later stage the influence of matter becomes stronger and stronger, and we come from this isotropic origin to the present, isotropic state. What about the future? The Einstein equations are nonlinear. Our result shows a singular behavior is possible, but a nonsingular solution is also possible."

Misner told us that because the mathematics is completely symmetric between the beginning and the end, once the universe changes from its present expansion, a singularity will occur in the future. However, the transition from expansion to contraction is not a clear prediction of the theory; it only occurs in closed models.

Landau Institute. Despite the fascinations of cosmology, Khalatnikov has also been interested and active in quantum field theory, and most of all, solid state. For twenty years he collaborated with Landau, until the automobile accident in 1962 that ended Landau's professional career. They both worked in the Institute for Physical Problems, headed by Peter Kapitsa. "Kapitsa discovered superfluidity and Landau explained it," Khalatnikov said. From the beginning Khalatnikov specialized in superfluidity: he wrote a book in the Frontiers in Physics series, "Introduction to the Theory of Superfluidity" (Benjamin, New York).

When it became clear that Landau would not recover, a group of his collaborators at Kapitsa's institute decided to found a new institute, and after his death it was named in his honor. The founders were: Khalatnikov, Alexei Abrikosov, who specializes in solid state and high-energy physics, Igor Dzheleshinski, well known in theory of magnetism and problems in statistical physics, and Lev Gor'kov, one of the leading physicists in superconductivity.

"Then some people from different places joined our group: Mark Az'bel is well known in theory of metals and wave propagation in metals. Anatoly Larkin is a universal man, working most recently with Lev Aslamazov (a young man from our institute) on the influence of fluctuations on the resistivity of superconductors near the transition point (paraconductivity).

"Emmanuel Rachba is an expert in theory of excitons, semiconductors and ionic crystals. Gerasim Eliashberg is a very talented man, who works in nonstationary properties of superconductors, collaborating with Gor'kov. Valery Pokrovskii (who came to us from Novosibirsk) works in high-energy physics and superconductivity; his most famous work was with Alexander Patashinskii—some of the first work on theory of phase transitions was done by them."

Dzheleshinski's work on high-tempearture superconductors has been significant, Khalatnikov noted. William Little had suggested one could make organic-type superconductors with high transition temperature, using a one-dimensional polymer. Then Pierre Hohenberg, basing his work on that of Nikolai Bogoliubov, showed that one cannot achieve superconductivity in one or two dimensions. But Dzheleshinski showed one can have some systems close to one dimensional (in which the interaction is much stronger in one direction than in the others) that could be superconducting at high temperature.

The institute has about 11 or 12 men with doctor's degrees (roughly equivalent in prestige to being a fellow of the American Physical Society); it has around 20 "candidates" (roughly the same as our PhD), about 15 graduate students and some undergraduates. The institute has the right to give scientific degrees and diplomas. Its location, Chernegelovga (it means a small black hat) is a new scientific center, which contains a few different institutes—physics, solid state, chemistry. —GBL

References

1. V. A. Belinski, I. M. Khalatnikov, Zh. Eksperim. i Teo. Fiz. **56**, 1700 (1969); Zh. Eksperim. i Teo. Fiz., December 1969.
2. C. W. Misner, Phys. Rev. Lett. **22**, 1071 (1969); Phys. Rev. **186**, 1328 (1969).

SIN to Begin Accelerating Before the End of 1973

SIN (Schweizerisches Institut für Nuclearforschung, or the Swiss Institute for Nuclear Research) has begun to prepare the site for its meson factory at Villigen near Zurich. The design of this machine was recently discussed by Jean-Pierre Blaser. A variable-energy cyclotron will accelerate pro-