> **The birth of a star is a violent and chaotic event, with gas flowing in and being ejected outwards at speeds up to hundreds of kilometres per second. The formation of a star is almost always accompanied by the formation of a planetary system"**

A star is born: understanding the physics of star formation

Understanding the violent and chaotic processes that characterise the birth of new stars is one of the biggest challenges in contemporary astrophysics. While advances in infrared detection technologies have made it possible to observe aspects of the star formation process directly, there are still many mysteries surrounding the exact physics involved. **Dr Christopher McKee,** at the University of California at Berkeley, has been developing simulations to unravel these complex processes to understand exactly what triggers the formation of these celestial bodies.

Stars are born out of diffuse molecular clouds of gas, in regions of space known as 'stellar nurseries'. These gas clouds contain the hydrogen and heavier elements that provide the fuel source for the star's lifetime.

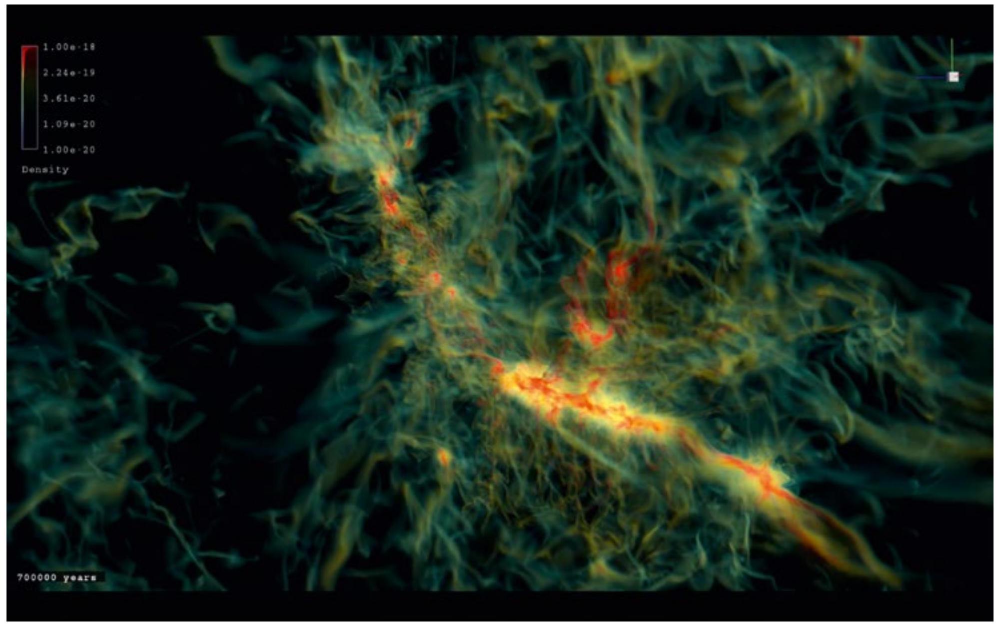
These molecular clouds can be in an approximate equilibrium between the forces acting to expand the cloud and those trying to collapse it (primarily gravity). However, if this equilibrium is perturbed, either by an external force, such as a supernova explosion, or by the cloud becoming sufficiently massive, the molecular cloud begins to undergo gravitational collapse.

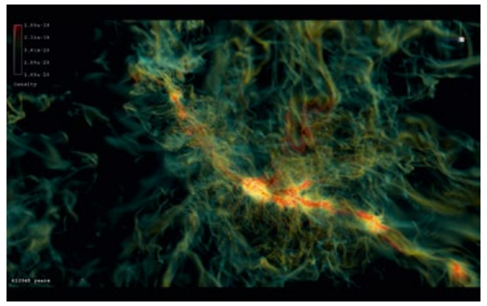
While this collapse occurs, the cloud can fragment into smaller masses. As stellar-mass fragments collapse, the temperature rises, and eventually the hot gas inside is at a high enough pressure to stop further gravitational collapse. The star then begins its life as a protostar that continues to grow by accreting the remaining mass from the fragment and possibly additional mass from the surrounding medium. Much of the gas that accretes onto the protostar does so through a disk, and planets can form during the late stages of this process.

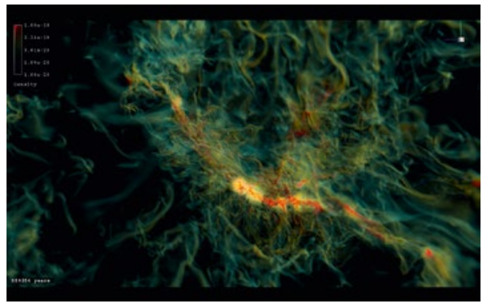
The star-forming region Rho Ophiuchi is located just 400 light years from Earth. Image by Rogelio Bernal Andreo

However, not all of these molecular clouds end up forming new stars, and not all the mass in a star-forming cloud goes into stars. What determines when and where stars form, and what determines their masses? The fundamental physical processes underlying star formation are only partially understood. These processes interact in complex ways that cannot be accurately described with pencil and paper calculations, and star formation can never be studied in the laboratory because gravity is too weak.

This is why Dr Chris McKee and his team of researchers at the University of California at Berkeley are interested in finding ways to simulate these processes on supercomputers and further our understanding of both how and why these events occur. These simulations can take over 1000 hours on 1000 processors acting in parallel on a computer. However, even such enormous simulations cannot follow the full range of scales, from a

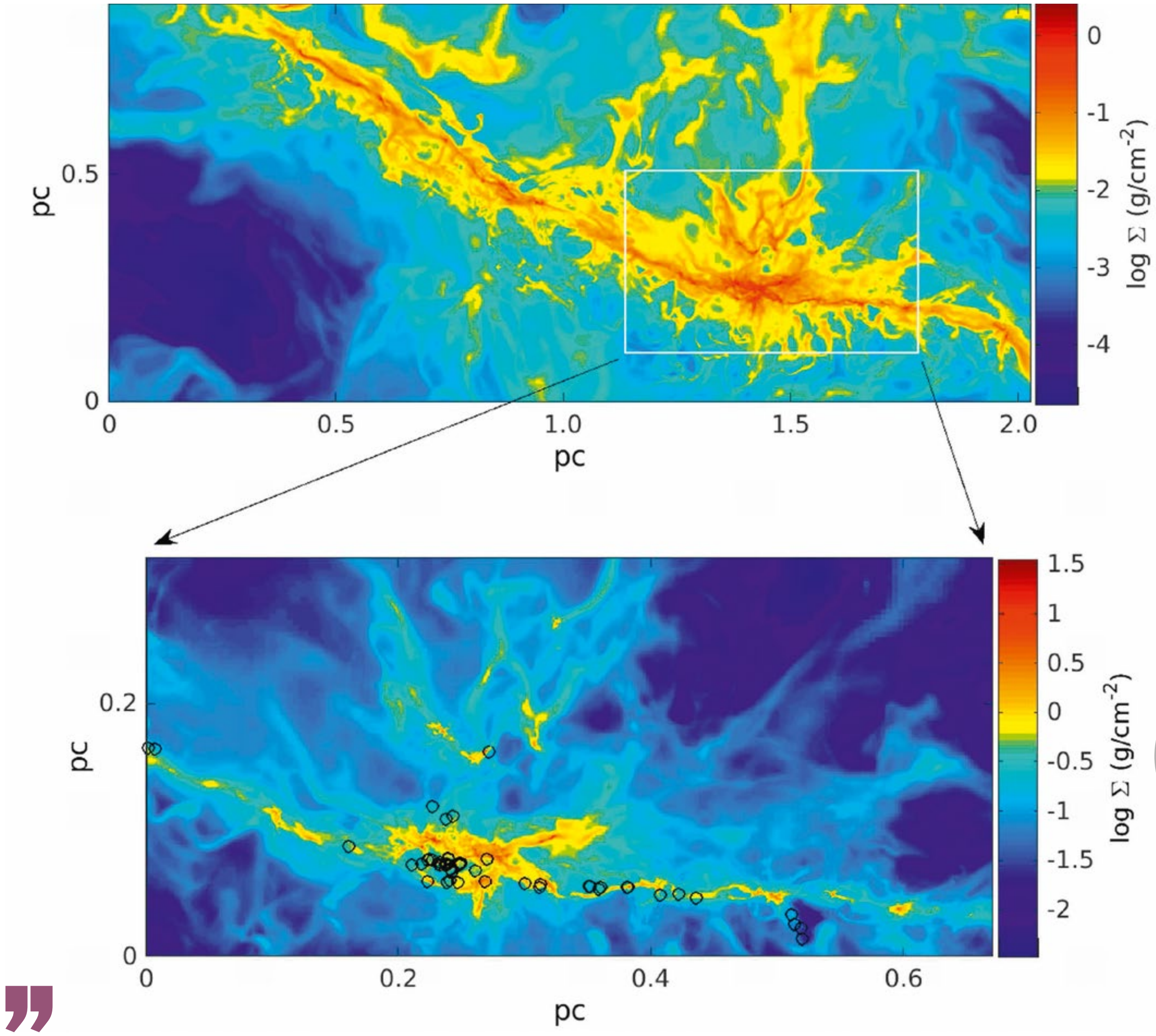






Above and left: Images prepared by David Ellsworth and Tim Sandstrom from a simulation by Pak Shing Li showing 350,000 years of evolution of a giant molecular cloud.
Right: A map of the amount of gas along each line of sight in a simulated filamentary molecular cloud that is hundreds of times more massive than the Sun, with a closeup view of the region where two parts of the cloud are colliding. The protostars that have formed are indicated by black circles.

> **Stars are rarely born as isolated individuals; instead entire clusters of stars might exist within one encompassing molecular gas cloud**



gas cloud light years in diameter to a star only light seconds across, so the accuracy of the simulations increases as computers become more powerful.

THE SIZE OF STARS

One aspect of star formation that Dr McKee is particularly interested in is the initial mass function (IMF). The IMF describes the initial distribution of masses in a newly formed stellar system, and what is very unusual about the IMF is that it appears to be about the same for almost all the stellar systems that have been observed.

The IMF is of great interest to astrophysicists as, if it were well-understood, it would shed light on how the stars formed and on how the conditions under which stars form shape their future. Stars like the Sun live for about 10 billion years, the least massive stars, about a tenth the mass of the Sun, live 100 times longer, and the most massive stars live for only a few million years. Because massive stars live so briefly, they burn brightly and have a powerful effect on their surroundings, culminating in a gigantic explosion – a supernova. The IMF determines how much material will be locked up in long-lived stars and how much goes into the massive, short-lived stars that create the heavy elements. The typical star – one at the peak of the IMF – has a mass only a few tenths the mass of the Sun, and a question of particular importance is, what determines that mass? Recent work by Dr McKee and his collaborators suggests that the observed peak in the IMF is due to heating by the accretion of matter onto the protostars, which limits the fragmentation processes in star formation.

STELLAR CLUSTERS

Most stars are formed in stellar clusters, which are groups of stars that are sufficiently close to feel the effects and forces of their neighbouring stars. These clusters can involve thousands of stars, and in extreme cases over a million stars. Clusters can be held together tightly by the effects of the gravitational force, or they can be more loosely bound, so that they dissolve as their natal gas is dissipated or when they intercept another molecular cloud.

Dr McKee has been working on models to account for not just the formation of individual stars, but how entire clusters form. Just as there is an IMF for stars, there is an IMF for clusters that also needs to be understood.

THE FIRST STARS

The first stars in the universe formed shortly after the Big Bang out of gas that had no heavy elements such as carbon, oxygen and iron, all of which are made in supernovae that occur at the end of some stars' lives. No stars without any heavy elements have ever been observed, which most likely means that the first stars were sufficiently massive – more than about 80% of the mass of the Sun – that they died before now. Another important difference between the first stars and subsequent generations of stars is that it is believed that during the initial stages of the formation of the first stars, it is the gravity of dark matter that initiates gravitational collapse. Calculations have shown that this naturally leads to more massive stars, but the IMF of these stars remains uncertain. Dr McKee and his collaborators are simulating the formation of the first stars in order to shed light on this problem.

All of Dr McKee's work contributes towards a future in which it would be possible to accurately predict when and where stars are likely to form, and what the outcome will be. This work is part of the grand scientific quest to understand our origins

Detail

RESEARCH OBJECTIVES

Dr McKee's research focuses on the scientific theory behind star formation. In particular, his research looks at the formation of both low-mass stars such as the sun and high-mass stars, the determining factors behind the rate of star formation in galaxies, and the processes governing the formation of the first stars in the universe.

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- Richard Klein
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- Eve Ostriker
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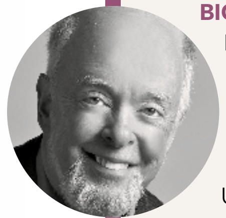

BIO

Prof McKee completed a PhD in Physics at UC Berkeley in 1970. After several years as an assistant professor of Astronomy at Harvard University, he joined the Physics and Astronomy departments at UC Berkeley, where he has remained since 1974. Prof McKee is a member of the US National Academy of Sciences.

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