S GEORGE DJORGOVSKI: OK. Let's move on now to the other use of star clusters, which is how to probe stellar dynamics. And they provide a really neat laboratory for Newtonian dynamics of many, many bodies. Solar system is good when you essentially have a whole lot of two-body problems because only one mass matters, the one in the middle. But here, all stars are more or less equal.

And you can think of it as a scoop of self-gravitating molecules or atoms subject to statistical mechanics. So, in fact, what will happen is the stars closest to the core will be those with lowest energy. They sink down to the bottom of the potential well. Stars that have higher energies will be able to go to the outskirts. Because there is a Maxwellian distribution of velocities, there will be many more low velocity ones than tails of the high velocity ones. And so, therefore, the cluster will be concentrated in the middle.

Now, they do not start nice and round like this. You've seen pictures of open clusters. They're kind of irregular. So what happens is that, as stars go by each other, they exchange energies until the whole thing kind of comes into thermal equilibrium. Now, there is a certain length of time that's required to do this. Usually, it's like hundreds of millions of years.

And if you can wait long enough, then the cluster will relax into what will be, essentially, a gas of stars interacting through their own gravitational field. But other interesting things happen as well-- so-called core collapse. And then clusters don't live in a vacuum. Well, they do in a sense. There are other things near them, most notably, their host galaxy. And interaction with the gravitational field of the host galaxy can also change their evolution in profound ways.

So here's some of the basic numbers. Typical open cluster has 100 stars. A globular cluster's 100,000. An elliptical galaxy, more like 100 billion. The typical sizes in parsecs are not terribly different. I think for elliptical galaxy that's a mistake. It should be more like 1,000, 10,000. Typical velocities are given here.

When you compute how long it takes for an average star to cross that particular object, millions of years, for open clusters, few million years, globular clusters, even less, galaxy, a lot. But then when you do proper dynamical computation to figure out how long will it take for this gas of stars to come into their thermal equilibrium, to relax, turns out those numbers are some millions of years for open clusters, hundreds of millions for globular clusters and many orders of magnitude more than the age of the universe for elliptical galaxies.

So elliptical galaxies got their nice shapes for some other reason, which is actually now called violent relaxation. But as far as star clusters are concerned, these are the relevant numbers. Now, notice that for open clusters, the crossing time, the relaxation time, and the typical ages are kind of comparable. Which means that they're going to evolve very rapidly on their own time scale and essentially evaporate.

For globular clusters, you have this inequality that it takes much longer time to relax than just to cross the cluster. And that's much shorter than the age of the universe, an evolutionary time scale. So you expect to see a broad range of different dynamical states, which is, in fact, how things are observed.

So this is probably a familiar phenomenon. We talked about this in the context of collapsing protostars or ignition of stars. And you can think of it, again, as follows-- say core shrinks a little bit, gets a bit hotter because now there is more binding energy so you have to increase kinetic energy of stars there. Faster stars will then escape. And then because they took away kinetic energy, core is going to shrink some more.

So this is specific to all systems bound by positive interaction like gravity. The hotter they get, they're going to get even hotter. So it's like negative specific heat. If you take away energy from them, they get hotter. And so if you leave cluster on its own, here is a plot from a theoretical model of, say, density versus radius on a log-log scale. It's just going to keep shrinking and shrinking and shrinking. In principle, it could make a big black hole in the middle.

So this is called a gravothermal catastrophe. Now, in stars, thermonuclear reactions ignite, provide the energy that replenishes kinetic energy that was lost by fast particles, and that stops the collapse. In globular clusters, there are no thermonuclear reactions, but, turns out, there is a source of energy. And that's hard binaries.

So if you have a star passing by a binary star, they'll interact in some way that depends on the input vectors and so on. And the passing by star can maybe gain some kinetic energy at the expense of the binary or maybe give some kinetic energy to the binary, make it a little looser, and everything will happen. But it turns out that tightly bound binaries, so-called hard binaries-- their binding energy is much larger module of the sign than the average binding energy in a cluster.

But there are excellent ways of giving away the energy. Then they get a little tighter. So the binary keeps shrinking slowly, giving a little kick to stars that come by on average and so, in a sense, serves as a source of energy. Now, if you start collapsing the cluster, you are going to generate some binaries because of tidal capture. Some of them will be already there present.

And so, in some sense, the cluster will then generate it's own source of energy. So this has been occupying theories for quite a long time. Now, the external processes are also important. You look at a globular cluster. It's zipping around the galaxy in some distant orbit, crosses the disk.

Every time it crosses through the disk or the bulge, it undergoes a little shock. It's the same thing as when you're driving over a speed bump. Suddenly, there is a little extra impulse of energy. And the faster you go, the more you're going to bang your head into the car. So the same thing now happens to the clusters.

As they go through these passages through the disk, they're going to get little boosts of kinetic energy. And some stars will then gain enough kinetic energy to escape. Even if that wasn't the case, in terms of the shocks, just because of the random distribution there would be some stars in the tail of the Maxwellian distribution that would get far enough-- they would get so far so that the gravitational field of the galaxy is now stronger than the one over the cluster.

Once that becomes the case, they will now belong to the galaxy. So stars essentially evaporate from clusters, just like hottest molecules will evaporate from liquid, stars evaporate from star clusters. And in case of the disk clusters, those tidal shocks are provided by passing by giant molecular clouds, which tend to have masses like million solar masses, and they can give a little kick to the open cluster stars. Which is why open clusters get dissolved so quickly.

So stars from globular clusters end up populating galactic halo and bulge. Stars from open clusters get to populate galactic disk. We now think that every star was born in a cluster of some sort some time ago. And many of those clusters have been completely evaporated away. This is how galaxies are made.