S. GEORGE DJORGOVSKI: So let's look in a little more detail at exactly how is this luminosity produced and how is that energy actually released out. The first thing that is important to know is that it's probably the mergers of gas-rich galaxies that are fueling a lot of the, at least, spectacular quasar activity. It doesn't have to deal was a merger. For example, a Seyfert galaxy can be a spiral disk, a normal spiral otherwise. There's just enough interstellar medium that flows to the middle to fuel the active nucleus.

But you may remember when we talked about merger simulations, that stars do their thing, but gas loses energy much more efficiently because of dissipative processes. Gas clouds collide. And gas sinks to the middle, much more so than in stars. We can make a very dense blob. And if there is a black hole to be fed, that can provide perfect fuel for a very luminous episode.

And so we think that actually quasars are not always on. They last may be some tens of millions of years during one of these merging events. And then there'll be another one, and another one later on. And so there is a lot circumstantial evidence from pictures of quasar host galaxies, like these from Hubble Space Telescope, that show that there looks like some of the dynamical interactions that we see.

So, in fact, accretion is the only plausible way we have to power objects that are this luminous. And the material comes from sufficiently a large radius-- so compared to the binding energy right near the black hole, its binding energy starts at essentially 0. And so if you go from tens of kiloparsecs down to microparsecs, you can, in principle, get rid of all of them binding energy. All of the MC squared can be turned into luminosity.

Now, that doesn't really happen. If you could do it directly to the Schwarzschild radius, you could really radiate away 100% of the rest mass energy. But in fact, no, they settle into this accretion disk. And the accretion disk has an inner edge, which is the smallest stable orbit.

Now, this is where the differences between Einstein gravity and Newtonian gravity come in. That for Newtonian gravity, there is no such thing as a smallest possible orbit. If you have point masses, you can put them as close together as you wish. This is not the case in general relativity.

So there is a smallest possible orbit. And its radius is several times the Schwarzschild radius. And it's different for spinning black holes and for stationary holes. It's closer in for spinning black holes, which means that a larger amount of rest mass energy can be radiated away by a spinning black hole. And so that's the efficiency factor, which is maybe few percent on average. And so a few percent of the rest mass energy of the in-falling material gets turned into radiation.

Now, how luminous can you make them? Well, remember adding to the luminosity, which is the limit of the stellar luminosity-- this is the luminosity at which the radiation pressure balances the gravitational pull of a star. And if you have more radiation pressure, that blows away. And so that's what sets the upper limit to the massive stars.

Now, there is no upper limit to the massive black holes. But it tells you that for a given mass black hole, there is the maximum luminosity it can have if it's accreting isotropically. And that's the Eddington ratio. So now we think that, in fact, most of the active nuclei, when they're on, they're accreting at nearly the Eddington rate, as fast as they can.

And if you ask, well, how much accretion do you need to produce these luminosities that we see, well, the answer is you need millions to hundreds of millions of solar masses. And that's, in fact, the kind of masses that we infer from dynamical measurements. So it all kind of makes good sense.

Now, because Eddington luminosity is proportional to the accretion rate, it's also proportional to the mass itself. This is going to be an exponential process because the bigger the black hole you make, the larger the luminosity you can have, the larger accretion rate you can have. And so, in principle, if you don't put any brakes on it, black holes would grow exponentially and get exponentially more luminous. Now, that doesn't happen because at some point, they run out of fuel. But whenever they do happen, that seems to be the case.

And so where does this energy actually come from? Well, a lot of it comes from just thermal energy in the accretion disk. That material is now releasing so much binding energy, that it's very, very hot. And temperatures inside accretion disks can be millions or in ten of millions of degrees close in, less as you go further out. So the emission is a combination of many, many black bodies of different temperature.

In addition to that, if you are accelerating electrons with magnetic fields, they're going to emit synchrotron radiation, which you may recall from the early parts of the class. And usually the distribution of energies of electrons, it tends to be a power law, which also then tells you that the spectrum of the emerging radiation will be a powerful law. It will go a frequency to some power. minus alpha typically, because it's minus first power of frequency, or something like that.

Not for the entire range. At very high energies, you get a cutoff because electrons are losing energy so rapidly. At low energies, you get a cutoff also because those same electrons can then absorb energy emitted by the faster electrons. By saying radio regime is sometimes all the way to X-ray regime, you can have something that is close to power law.

So this is a known thermal emission, unlike black body. And the overall emission from quasars is a combination of these components.

So here is the spectrum, the average spectrum for quasar, in the optical and ultraviolet. And in fact if you draw a line through it, you can see that this log plot, that it's a straight line, describes continuum. So it's a power law continuum, at the top of which there are some bumps, which may be thermal emission, plus the emission lines. And the cutoff in the ultraviolet is due to the gas between you and the energy.

So this explains this plot that I've shown you earlier, why there is such a broad and nearly flat, but not exactly flat, distribution of power emitted per log frequency interval versus frequency. So it's kind of flat. And those are bumps on it. And those bumps are thermal emission.

There is thermal emission from the accretion disk. That's called the big, blue bump. There is also thermal emission from the dust around the whole thing. That's called the big, red bump. And in radio, it's just the synchrotron emission from the electrons. In X-rays, it's mostly synchrotron emission from the electrons, but at very high energies.

So what about those jets? This is the cartoon version of what happens. You have magnetic field that's threaded through the accretion disk because it was frozen in the plasma that collapsed down or maybe even inside plasma that fell into black hole. Because it's a long range interaction, you could have magnetic lines of force go through the black hole.

And it gets wound up by the spin, meaning the field strength goes way up and acts just like an accelerator accelerating electrons along those lines. So this has been observed, mostly in the radio. And those jets are persistent over very large scales in radii.

Now what's shown here is a map of M87, of active galaxy in Virgo Cluster. And if you zoom in from a very large scale to a smaller scale, and zoom in, and zoom in, and zoom in, you always see that there is always a jet from a central source point, taking one direction.

So radio jets are very common. The reason why they're so persistence is that, well, particles are moving at the normal speed of light. So they will carry on in their momentum, right?

And in the case of M87, and some others, they also shine in visible light and X-rays as well. They're not uniform. They're all blobs. And we can actually see them move with observations spaced in time.

So that is now very commonly seen everywhere. And there is one of the nearby active galaxies where you can actually see the obscuring torus, so proposed on an elliptical galaxy. And there is a point source in the middle. And radio jets have come out orthogonal to the torus. So the whole picture makes a lot of sense.

Now in the 1970s, people noticed something else fun. That, gee, you can see sometimes distinct blobs and they're moving out. They are just blobs of plasma that have been accelerated out. And they found out that oftentimes they move faster than the speed of light. Now, that was kind of a problem, right?

And so what was finally realized is that this is not real. This is an optical illusion that's specific to relativistic motions. That clocks tick slower over there. And under the right projections, things will look like they're moving faster than the speed of light to you. But over there, they're just under the speed of light. And people here at Caltech have played an important role, Tony Readhead, Marshall Klein, and Roger Blandford, in understanding how this happens.

Now, we've seen this same thing happening in what we call microquasars, which are the little black hole binaries inside the Milky Way, that operate pretty much in the same way, only on scales of millions of times smaller. So that's what they call superluminal expansion. Material is not really moving faster than the speed of light. The projection looks like it's moving faster the speed of light.