[Email from Ramesh Narayan to all webinar attendees, Sept 2020]

Dear Friends,

I apologize in advance for this group spam!

First, I wanted to thank everyone for attending the Accretion Physics Webinar and making the discussion session so lively with your questions.  I will provide more answers to your questions below, but first I would like to remind those who have not yet responded to the Post-Webinar Survey to please do so as soon as possible. The web link is:

<http://bit.ly/BHPIRE-Sep20>

Having a strong response from attendees allows us to make the case to our funding agency that the BH PIRE program is making good use of the financial support they provide us. Thanks!

Rosie Johnson forwarded the complete list of questions in the Chat and Q&A. I answered several of these questions during the webinar, and I will repeat my answers here. I will also answer other questions that we did not have time to address.

I know that email is not the right medium for this exchange and we should probably use Slack. However, that technology is beyond me, so please excuse this old-fashioned communication channel!

Chat:

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08:32:07                From CANER UNAL to All panelists : is Rs in the plot mean R\_schw?

Yes. In the article with Quataert, we used the Schwarzschild radius, R\_S = 2GM/c^2, as our unit of length, where M is the black hole mass. Many other technical articles tend to use the gravitational radius, R\_g = GM/c^2, as the unit of length.

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08:40:42                From Hyerin Cho to All panelists : If the temperature is high and the cooling rate is very low, wouldn't this create an instability of a runaway increase of the temperature?

Yes! The gas in a hot accretion flow (or ADAF) is in a permanent state of thermal instability. It takes whatever heat is available and becomes as hot as possible. In practice this means that the temperature becomes "virial" i.e., kT ~ GMm\_p/R ~ (few x 10^12K) x (R\_S/R), where m\_p is the proton mass. By the time a proton reaches a radius R, it has released potential energy equal to GMm\_p/R and it converts most of this energy into heat. As the proton falls to smaller radii, it converts more potential energy to heat and becomes hotter. Thus, there is indeed a runaway thermal instability, but it is accompanied by accretion to smaller radii, so at each stage the gas is roughly at the local virial temperature.

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08:47:25                From Sophia Sanchez-Maes to All panelists : What is the transition to red signify in that animation?

The red regions correspond to negative energy, i.e., where the binding energy is greater than the rest mass energy of the fluid. This very counterintuitive situation occurs only around compact spinning objects like a Kerr black hole, and even then only inside the ergosphere. The effect was discovered by Penrose in 1969, who showed that it allows energy and angular momentum to be extracted from a spinning hole. Penrose's original idea for energy extraction was based on particles, and is not considered important in practice. Blandford & Znajek (1977) came up with a scenario involving magnetic fields, where Penrose's ideas are realized under astrophysically more plausible conditions.

The animation from Semenov et al. (2004) which I showed in my talk illustrates the Blandford & Znajek mechanism  in a highly idealized situation. It shows how frame-dragging generates a helical pattern and causes energy to flow out along the jet. The negative energy regions, shown by the red segments, fall into the black hole. Correspondingly, positive energy flows out to infinity along the helical wave in the jet. There is a brief discussion (not much more than what I have written here) in the review by Narayan & Quataert (2005), Fig. 4.

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08:49:14                From Saurabh Saurabh : Does this mean that the BH’s angular momentum should come down?

Yes, the BZ process removes angular momentum from the black hole. Thus it causes the black hole to spin down.

One consequence is that any given jet system in the sky will ultimately run out of black hole spin energy when the black hole spins down enough, and the jet will shut off. To revive the jet, the black hole needs to be spun up somehow. A likely scenario is that the black hole goes through a stage of thin disk accretion, during which the accreting gas adds angular momentum to the hole. If the system subsequently switches back to a hot accretion flow, then it will have a strong jet, but again only until the black hole loses the spin energy it acquired during the thin disk stage.

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08:57:20                From Saurabh Saurabh to All panelists : When the magnetic field is near the BH (in the movie) the cork structure, does the angular momentum reduced or some exotic physics happening there?

As I wrote above, the energy source is the spin energy of the BH, so the black hole spins down, and in that sense it is nothing exotic. But I think the process itself is exotic: extracting spin energy via frame-dragging of the space around the spinning hole!

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09:00:32                From Sophia Sanchez-Maes to All panelists : We’ve observed NS spin down - can we do the same for a BH?

The time scale on which either neutron stars or black holes spin down is very long (millions to billions of years). The only reason we are able to measure spin down in neutron stars is that the periodic pulses in these objects make them perfect clocks, so we can make extraordinarily precise measurements of pulse arrival times

Unfortunately, we do not have similar periodic pulses in black holes, so that approach is ruled out. There are so-called quasi-periodic oscillations (QPOs) in some accreting black holes, but they have very low quality factors and are not suitable for precise timing. Also, we do not understand the physics of QPOs, so we do not know how to translate the period of a QPO to the rotation rate of the black hole.

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Q&A:

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| Question |  |
| is Rs in the plot mean R\_schw?  See above  ------------------------------ |  |
| also Ramesh mentioned Mdot can grow upto Ledd and extra energy will be given  to gas, what sets the accretion rate Mdot?  The accretion rate is set by mass supply at large radius, i.e., it is an external  boundary condition. Depending on how much gas is supplied from the outside,  Mdot is either large or small relative to the Eddington rate Mdot\_Edd.  One additional complication: If the accretion flow loses a lot of mass along the  way via a wind, which is plausible whenever the accretion is advection-dominated,  then the actual Mdot into the BH may be a lot less than what is supplied on  the outside.  ------------------------------ |  |
| also if gas is around 10^12 K~10^8eV~100MeV, should not we see electron  positron pair production to cool faster?  In hot accretion flows (low Mdot systems), the density is too low for substantial  pair production to occur. If the density is large enough for strong pair creation,  there will be catastrophic cooling and the gas will switch to the cool thin disk  state.  It is believed that pair production does occur in the jet region, where strong electric  fields cause particles to be accelerated to highly relativistic velocities. The physics  of pair creating in the jet is not well understood.  ------------------------------ |  |
| Does this mean that the BH’s angular momentum should come down?  Yes, see earlier.  ------------------------------ |  |
| magnetic field is sourced by disk, and disk;s inner layers is determined by spin,  so spin should influence B as well  Yes, there is certainly some back-reaction of the black hole spin on the magnetic  field strength in the disk.  In  terms of the magnetically arrested disk (MAD) limit  Tchekhovskoy has found that, in the case of hot accretion flows, the maximum  magnetic flux for a given Mdot is somewhat smaller for rapidly spinning holes  vs slowly-spinning holes. On the other hand, in some unpublished simulations I  ran on super-Eddington disks (which are also ADAFs), I found the  magnetic flux to increase slightly for rapidly spinning holes. In either case, the  effect is fairly modest (less than a factor of 2).  ------------------------------ |  |
| I recall a controversey about the Blandford-Znajek process interpretation that  was about the famous membrane paradigm which treated the event horizon like  a spining conductor. There was an argument that the energy in the BZ process  was actually coming from the light cylinder and not the event horizon...was this  controversey ever resolved?  This is an interesting question. I myself do not understand the original controversy.  I have assumed that it is not a serious problem since BZ seems to work fine in  numerical simulations. But somebody should now go back, study the original  arguments, and check if  simulation data can be used to shed light, e.g., by  explicitly identifying a fallacy in some of the previous arguments.  ------------------------------ |  |
| Can the accretion energy be radiated as Gravitational Waves?  In principle yes, but it needs a lot of mass in the accretion disk. Most systems  have far too little mass for gravitational radiation to be important. The exception  is accretion disks in collapsars, where a solar mass or more might accrete in less  than a second. These systems do have enough mass for gravitational wave  emission to be important, though energy loss through neutrinos might also be  equally important.  ------------------------------ |  |
| Can we have a understanding for the same with NR Black holes?  I am not sure I understand this question. If NR refers to Reissner-Nordstrom (RN)  black holes, I think there ought to be similar energy extraction via charged particles.  The physics is likely closely related to the Penrose process, but I am not familiar  with any discussions in the literature.  ------------------------------ |  |
| Second question: You stated the thin disk has very little pressure. There have  been some recent papers about how stars & black holes could accrete very  rapidly inside a thin disk of an AGN, but if the pressure is low how could the  gas get forced onto these objects so rapidly?  The gas in a thin disk has low pressure because of low temperature, but it  has high density. So accretion of gas from a thin AGN disk on to a star or a  small black hole that happens to be in the disk is possible because of the high  density (and also because the relative velocity between the star and the gas  is low for favorable orbits).  ------------------------------ |  |
| Ramesh mentioned the two-temperature model in one slide. What would be  the observational signature of the model (by EHT)? What do we expect to  observe to prove it?  I cannot think of any simple way of verifying that the accreting plasma in an EHT  source is two-temperature, but it would be great if we could do it!  Observations can give a reasonably good estimate of the electron temperature,  but  measuring the ion/proton temperature is tough. If proton collisions  produce  a sufficient number of pions, and if we are able to observe radiation from  pion decay, there may be a (model-dependent) way of  estimating the proton temperature. Or, if we could independently estimate the gas  pressure via observations,  and if the corresponding temperature is much larger  than  the electron temperature, then we could plausibly argue that the proton  temperature has to be much larger than the electron temperature.  ------------------------------ |  |
| Is creation of hot accretion related to increasing entropy?  This is a beautiful question! I have for a long time thought that the switch  from cold to hot accretion should be understood via entropy.  Certainly, for a given Mdot and R, the entropy of the gas in the hot solution is  much greater  than the entropy of the gas in the equivalent cold solution.  If we were dealing with  equilibrium thermodynamics, that would be the end  of the story and we would have explained why hot accretion is preferred.  Unfortunately, we have a dynamical system in which a given fluid element  never reaches equilibrium. Instead, it constantly evolves as it accretes towards  smaller radii. It keeps receiving heat, keeps increasing its temperature, etc.  We need to consider rate equations. We must understand in particular how cold  gas "evaporates" to form the hot state and how quickly this can happen. I am  sure there are methods based on non-equilibrium thermodynamics which  might be suitable to analyse this problem, but I am not familiar with them.  ------------------------------  Sorry this email ended up being so long. Thank you everyone,  Ramesh Narayan |  |