Single and binary Black Holes and their active environment

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1 Abstract

In this short review we describe some of the latest endeavours to understand the activity around Black Holes. Black Holes have now been observed on many mass scales, from about 5 solar masses all the way to almost $10^{10}$ solar masses. Stellar size Black Holes appear to exist all through galaxies, while more massive Black Holes appear to occur only in the centers of galaxies. First we outline some efforts to understand accretion disks and especially jets around stellar-size Black Holes, also known as microquasars. Here it has been possible to demonstrate that a large part of the electromagnetic emission observed can be interpreted as arising from the jet; this explains at once all spectral features and their variability. Second we dwell on the concept that merging galaxies naturally lead to merging Black Holes. Here we emphasize two aspects: a) the torque exerted by the binary Black Holes carves a torus like distribution out of the stellar population near to the Black Hole binary; the sub-population of red and blue super giants with stellar winds may have their winds turned into tails, which as an ensemble may make up the ubiquitous torus, inferred from X-ray, infrared and optical polarization observations. b) We consider the last stages of the Black Hole binary merger, taking into account the angle between the spin of the primary Black Hole, and the orbital spin of the second Black Hole. We show that the loss of orbital angular momentum is very strongly spin-dependent; for large angles between the two spins the angular momentum loss is strongly inhibited, allowing for spin flips of the primary Black Hole, as it merges to become the new combined Black Hole. This spin flip preserves a high angular momentum relative to the maximum allowed. This ensures that both before and after the merger the accretion disk may reach to very small distances from the central Black Hole, with very high local temperatures right near the base of the jet: This is especially interesting in the case that forming the jet requires the formation of an ADAF like ring near the inner edge of the disk, as suggested by some earlier work. It also may have consequences for the initial hadronic
interactions right near the base of the jet. Finally, this may also have important implications for the discovery of gravitational radiation bursts from the merger of black holes; the spin dependence needs to be taken into account.

2 Introduction

Black Holes have now been found on all mass scales, from stellar size to about $10^{10}$ solar masses. They are very common, with the more massive Black Holes all apparently occurring in the center of galaxies; almost all galaxies seem to harbour a central Black Hole. When they accrete, they display an enormous variety of phenomena, accretion disks, relativistic jets, broad and narrow emission line clouds, and tori of cold absorbing material. Since the stellar size Black Holes, in a mass range between about 5 and 10 solar masses, occur rather closer to us than any other more massive Black Hole with large accretion power, they can be used to study the underlying physics. So we discuss in the first part of this review some recent work, where we tested the hypothesis that the underlying physics may be similar, if not the same, on all mass scales of Black Holes. We find that stellar size Black Holes and their activity are well described by a scaled down version of the concept developed for more massive Black Holes. Then we move on to more massive Black Holes, and note that mergers of galaxies naturally lead to binary Black Holes. Binary Black Holes eventually merge, and when they merge, their spin becomes critically interesting for the last stages of their gravitational wave emission. In order not to explode the list of references, we have been very parochial and just mention our own work, and a few pertinent reviews, and some limited set of references.

3 Microquasars, Active Galactic Nuclei and High Energy Particles

In a series of papers Falcke et al. have developed a jet-disk-symbiosis picture. In these papers it was possible to show that with just mass and energy conservation and a few simple scaling arguments the emission from the jet and the disk could successfully be modeled; it was shown, e.g., that equipartition in the comoving frame turned out to be a good approximation, yielding the most efficient jet system. In the last three years we have been able to show that the jet-disk symbiosis picture developed is also applicable to the binary star Black Hole systems. These are stellar binary systems, where one partner is a normal star, and the other one a Black Hole. These systems are also known to exhibit an accretion disk, fed by mass transfer from the partner star, a radio jet, which is also relativistic, and therefore they have been dubbed “microquasars”, . There has been a lot of activity centered on such systems, e.g., , , , , , , , , , .

The recent observations of microquasars with the X-ray satellite CHANDRA provided a welcome opportunity to test the physical concepts of our jet-disk symbiosis concept originally developed for more massive systems. In the last three years we have been able to show that almost the entire electromagnetic spectrum can be described by emission from the jet, and only a small part of the observed emission arises from the accretion disk, and possibly from a small disk corona. The variability and the spectrum could be matched with a simple description of synchrotron and inverse Compton emission from the jet, using shock acceleration as one key concept, , . The model then indicates the location of the shock and its
physical parameters, as well as the phase space distribution of the energetic electrons and/or positrons. Fig. 1 shows one example for our spectral fits for a microquasar.

These successful and conceptually simple fits have now been extended to low luminosity Active Galactic Nuclei (AGN), [21, 30, 56, 32], and provide now a backbone for studying the hadronic interactions in jet-disk systems of all powers. Microquasars are now a very well-studied testbed for all processes expected to take place in very powerful sources, including high energy hadronic and leptonic processes.

3.1 Gamma Ray Bursts

Similarly, Gamma Ray Bursts provide one further test for Black Hole formation in stellar binary systems, and also for cosmological evolution, as we have shown and continue to investigate. One possibility to explain Gamma Ray Bursts is to adopt the existing binary systems such as SS433 as predecessors, a massive early type star in a binary system with a neutron star, which is surrounded by an accretion disk and produces a jet, [47]. In such a system all parameters are well known, there is little freedom as to the magnetic field strength and other key parameters of the system. When the neutron star is pushed over the brink of instability and becomes a Black Hole, a gigantic explosion pushes an ultrarelativistic shock wave along the pre-existing channel, the jet. It has been possible to show that the emission from this shock can explain all the gross features of Gamma Ray Bursts afterglows. Furthermore, connecting the star formation rate with the Gamma Ray Burst creation rate leads to a cosmological evolution as a function of redshift, which is sharply defined: It rises steeply to a redshift near 1.7, and declines only gently to higher redshift, in full agreement with the arguments from other wavelengths. Using thus the absolute scaling provided by this quantitative fit to the numbers - taking selection effects into account, following Petrosian, [44] - leads then to a determination of the possible contribution of Gamma Ray Bursts to the flux of cosmic rays, [48]: Both from Galactic sources as from extragalactic sources it is hard to see how their contribution could be significant.

3.2 Radio Galaxies: Ultra High Energy Cosmic Rays

This work leads to the possibility to verify again our concept that radio galaxies and their cousins, the relativistic jets pointed at us such as BL Lac type sources and GHz peaked sources, provide the highest energy particles known to us in the Universe, [2, 15, 5, 6, 4, 7]. All these emission processes are likely to involve hadronic interactions and will then be testable with very high energy neutrino observations, [27]. Fig. 2 shows the example of the Galactic center low luminosity AGN Sgr A*, see, e.g., [33]. Using the scaling of magnetic field strength with other signs of power leads to an estimate of the maximum energy of a particle that can be contained in the jet, along its length or in its head, the hot spot - if there is one. This suggests that about $3 \times 10^{21}$ eV is the maximum; allowing for some relativistic boosting this limit may extend to $10^{22}$ eV on the outside.

3.3 Scaling laws for jet-disk systems

What we learn then from applying the jet-disk symbiosis picture to microquasars, low luminosity AGN, and also high luminosity AGN is that the scaling laws are indeed a very
**XTE J1118+480 Model Results**

(Markoff, Falcke & Fender, A&A, 2001)

Fitting thermal "disk" inner edge ⇒ \( T_d = 1.7 \times 10^5 \text{ K} \)

\( L_d = 5 \times 10^{35} \text{ erg/s} \)

\( r_d = 750 \ r_g \)

\( m_d = 0.1 \)

**Jet parameters:**

- \( r_{noz} = 3r_g \)
- \( q_j = 0.01 \)
- \( Z_{sh} = 90 \ r_g \)
- \( \theta = 32^\circ \)
- \( T_e = 8 \times 10^9 \text{ K} \)

50% accelerated

Figure 1: Our jet-disk symbiosis model fitted to the CHANDRA data, using the microquasar XTEJ1118+480 as an example; we also show the geometry of the model.
Figure 2: Our jet-disk symbiosis model fitted to the CHANDRA data, using the low luminosity Active Galactic Nucleus in our Galaxy Sgr A* as an example; again we also show the geometry of the model.
good first approximation to the complex physics undoubtedly ruling the physics of the activity around single Black Holes. This will present a welcome basis to study further physical processes in relativistic jets, such as the acceleration of protons and other charged nuclei, possibly yielding the highest energy cosmic rays observed.

4 Binary Black Holes

Today the work by the Hubble Space Telescope has shown convincing evidence that almost all galaxies have a central massive Black Hole, e.g., [25, 16]. The mass of this Black Hole correlates well with the total baryonic mass of the old spheroidal stellar population, and correlates extremely well with the central velocity dispersion of the central stellar population, [22, 26]. In earlier work we have shown that such correlations can be readily interpreted as the result of the competition of star formation and accretion as a function of radial distance in the disk of a galaxy, when considered as a gigantic accretion disk, and subsequent mergers between galaxies, [54, 55, 53, 4]. As soon as two galaxies merge which both have central Black Holes, the two Black Holes spiral in towards each other under the rather strong influence of dynamical friction, with time scales of order $10^7$ to $10^8$ years. This inspiraling slows down considerably when the two Black Holes get as close as the core radius of the central star distribution, of order a parsec or so. Again, this a topic of wide interest, e.g., [37, 35, 34].

4.1 The Central Torus

From the early X-ray observations, [21, 13], the polarization of the broad emission lines, [1], and later the far infrared and submm/mm observations, it had been inferred that many, if not most AGN harbour a central torus of cool obscuring material, [8, 9, 51]; see fig. 3 for a sketch of the unified scheme to understand AGN. There are already a variety of models for this torus. First of all, one idea has been to identify this torus with the irregular ensemble of merger remnants of interstellar clouds, [52]; another was to use radiation pressure to hold up the torus material against collapse, [45, 46]. Also, a magnetic field model has been shown to be viable [28]. Here we show that a torus can be understood also as the sum of many stellar tails, drawn out from an ensemble of red and blue giant stars in a torus like geometry, [57, 58].

Such a torus like geometry for the stellar distribution is a natural consequence of the torque exerted by a binary Black Hole system, see figs. 4 and 5. The central stellar distribution is carved out into a broad belt, whose subpopulation of red and blue giant stars has their winds turned into tails by radiation pressure from the central accretion disk, see fig. 6. [59]. These winds and their dust may constitute the ubiquitous torus, see fig. 7. Interestingly, this concept leads to a variety of successful checks: first, the number of stars necessary to remove sufficient angular momentum from the central Black Hole binary is just about equal to the number of stars implied by the necessity to be geometrically and optically thick (using the cross-section of all the winds turned into tails). Second, a single stellar wind-tail seen along the tail can obscure the entire broad line region, thereby assuring a rather short variability time scale, and also allowing for the partial covering occasionally suggested by X-ray data. Third, the column inferred for wind-tails is of order $10^{23}$ to $10^{24}$ cm$^{-2}$, just as required by the X-ray data as well, [59]. On the other hand, the wind-tails exist only if there is sufficient radiation from the inner accretion disk; should that disk have turned to an ADAF, with
Figure 3: The basic sketch of a unified model to understand Active Galactic Nuclei, in a single Black Hole case. The scales are logarithmic, and the geometry is not fully mathematically self-consistent in order to help the eye. A spherical broad line cloud distribution should really look more like a square with smooth corners in such a graph, while the conical jet should be even closer to a rectangular triangle in such a graph, with the 90 degree corner at the origin.
Figure 4: The distribution of inner stars in the plane of the two Black Holes, showing the broad belt in its own plane resulting from the torque of the two Black Holes.
Figure 5: The distribution of inner stars in a plane containing the rotational axis of the orbit of the two Black Holes, showing the broad belt in a cross-section resulting from the torque of the two Black Holes.
Figure 6: A sketch of a stellar wind drawn out into a tail by the radiation field of the central accretion disk, jet-base and jet.

Figure 7: A cross cut of the imagined ensemble of all the stars with wind turned into tails constituting the torus.
4.2 Merger of two Black Holes: Spin-flip

In recent work we have expanded this concept to include the final stages of the merger, now between the two central Black Holes. Fig. 8 shows our basic concept of the spin-flip of two merging Black Holes, [10].

When the two Black Holes get sufficiently close to induce gravitational radiation, it becomes necessary to include the spin orientation of the orbit of the two Black Holes, and their intrinsic spin. Focussing on the more massive Black Hole, and treating the second Black Hole in a test particle limit, we have used a post-Newtonian approximation to derive the properties of the gravitational waves, and the reaction of the two orbiting Black Holes. The interesting question is whether the angular momentum transport by the gravitational wave emission will remove most of the orbital angular momentum of the secondary Black Hole. This would thus lead to a final merged Black Hole whose total angular momentum has a direction which is little modified from the pre-merger direction of the spin of the primary Black Hole. Also, one might expect that the spin as a fraction of the maximum allowed is decreased relative to the

little ultraviolet emission, such tails will not exist, and so while the torus configuration in the stellar distribution may exist, the obscuration may be quite different, certainly then with no associated far infrared emission.
Figure 9: The run of the energy for a test particle coming in along different orbital planes; the dark line represents the innermost stable orbit. The innermost stable orbit as a function of inclination has the shape of a symmetric gourd. This figure shows that upon passing the innermost stable orbit the energy loss gets very weak.

pre-merger state.

Our calculations have shown that the opposite happens, see figs. 9 and 10: the removal of orbital angular momentum has been demonstrated to have a very strong dependence on the angle between orbital spin of the secondary Black Hole and the intrinsic spin of the primary Black Hole. This dependence is so strong that the final Black Hole spin after the merger is not only turned around, but also remains high relative to the maximum spin allowed.

This shows that a merger of a maximally rotating Black Hole with a secondary Black Hole with an orbital spin axis which is in a very different direction can lead to a spin flip, with the new spin again near maximum. The key point is that the orbital angular momentum of the secondary Black Hole is not completely removed by gravitational waves, as one might have expected, see figs. 9 and 10. Of all proposed models, this, it turns out, is the best viable explanation for the X-shaped radio galaxies, [50].

There is an important consequence, that any accretion disk again may go very close to the horizon both before and after the merger, leading to a very high temperature near the inner edge of the disk, [12, 13], especially should the formation of the jet lead to an ADAF-like structure of that inner ring of the disk underneath the budding jet [12]. This may be important for the hadronic interactions in such a region. [6, 14].

Our recent calculations show that the spin dependence of the Black Hole mergers needs to be taken into account because it severely modifies the final gravitational wave emission. This may have consequences for the template used to look for the weak signal from Black Hole mergers.
Figure 10: The run of the angular momentum for a test particle coming in along different orbital planes; the dark line represents the innermost stable orbit. This figure shows that upon passing the innermost stable orbit the angular momentum loss gets approaches zero.

5 Summary

Black Holes occur on many mass scales, spanning a factor of $10^9$. We have shown that the basic underlying physics of the jet-disk-Black Hole system is very similar on all scales, from microquasars to the most powerful quasars. All appear to have a relativistic jet, a compact accretion disk, and jet powers often equivalent if not larger than the visible emission from the disk. When galaxies merge, then by necessity also two Black Holes form a binary, that in turn will merge after some time. The torque from this close Black Hole binary may produce a torus like configuration among the inner stellar population; the winds of the red and blue giant stars may constitute the torus, inferred from X-ray, optical and mm-observations. The final stages of the Black Hole merger turns out to be strongly dependent on the relative spin direction of the orbit and the more massive Black Hole. This may have relevance for any search for a Black Hole merger signal in gravitational waves.

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