NUCLEOSYNTHESIS IN ADVECTIVE ACCRETION DISKS
AROUND GALACTIC AND EXTRA-GALACTIC BLACK HOLES

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 Appearing in ‘Observational Evidence for Black Holes in the Universe’, Ed.
S.K. Chakrabarti (Kluwer Academic:Holland) p. 105 (1998).

1. Introduction

Many of the observational evidences for black hole rely on the fact that
the incoming gas has the potential to become as hot as its virial temper-
\[ T_{\text{virial}} \sim 10^{13} \, \text{K} \] (Rees, 1984). This flow is usually cooled down
through bremsstrahlung and Comptonization effects and hard and soft
states are produced depending on the degree by which this cooling takes
place (Chakrabarti & Titarchuk, 1995). The generally sub-Keplerian, ad-
vective flow after deviating from a Keplerian disk, especially in the hard
states, remains sufficiently hot to cause a significant amount of nuclear re-
actions around a black hole before plunging in it. The energy generated
could be high enough to destabilize the flow and the modified composition
may be dispersed through winds to change the metalicity of the galaxy
(Chakrabarti, Jin & Arnett, 1987 [CJA]; Jin, Arnett & Chakrabarti, 1988;
Chakrabarti, 1988; Mukhopadhyay & Chakrabarti, 1998). Earlier works
have been done in cooler thick accretion disks only. Below, we present a
few examples of nuclear reactions in advective flows and discuss the impli-
cations. Results of more detailed study could be seen in Mukhopadhyay &
Chakrabarti (1998) [MC98].

2. Physical Systems Under Considerations

Black hole accretion is by definition advective, i.e., matter must have radial
motion, and transonic, i.e., matter must be supersonic (Chakrabarti 1996
[C96] and references therein). The supersonic flow must be sub-Keplerian
and therefore deviate from the Keplerian disk away from the black hole. The
study of viscous, transonic flows was initiated by Paczyński & Bisnovatyi-Kogan (1981).

By and large, we follow C96 for thermodynamical parameters along a flow and Chakrabarti & Titarchuk (1995) [CT95] and Chakrabarti (1997a) [C97a] to compute the temperature of the Comptonized flow in the advective region which may or may not have shocks. According to these solutions, a black hole accretion may be thought to be similar to a sandwich whose sub-Keplerian flow rate ($\dot{m}_h$) in the ‘bread’ part progressively increases and that ($\dot{m}_d$) in the ‘meat’ part progressively decreases as flow moves in towards the black hole. Finally at $x = x_K$, the equatorial flow also deviates from a Keplerian disk and for $x < x_K$ the entire flow is sub-Keplerian. Among the major reactions which are taking place inside the disk, we note that, due to hotter nature of the advective disks, especially when the accretion rate is low and Compton cooling is negligible, the major process of hydrogen burning is the rapid proton capture process (which operates at $T \gtrsim 5 \times 10^8$K) as opposed to the PP chain (which operates at much lower temperature $T \sim 0.01 - 0.2 \times 10^9$K) and CNO (which operates at $T \sim 0.02 - 0.5 \times 10^9$K). The present paper being exploratory in nature, we do not include nuclear heating and cooling in determining the structure and stability of the accretion flow. We do not assume here heating due to magnetic dissipation (see, Shapiro, 1973 and Bisnovatyi-Kogan, 1998).

For simplicity, we take the solar abundance as the abundance of the Keplerian disk. Furthermore, Keplerian disk being cooler, no composition change is assumed inside it. In other words, our computation starts only from the time when matter is launched from the Keplerian disk ($x = x_K$). Most of the cases were repeated with initial abundance same as the output of big-bang nucleosynthesis (hereafter referred to as ‘big-bang abundance’).

According to CT95, and C97a, for two component accretion flows, for $\dot{m}_d \lesssim 0.1$ and $\dot{m}_h \lesssim 1$ the black hole remains in hard states. Lower rate in Keplerian disks generally implies a lower viscosity and a larger $x_K$ ($x_K \sim 30 - 1000$; see, C96 and C97a). In this parameter range the protons remain hot, typically, $T_p \sim 1 - 10 \times 10^9$ degrees or so. This is because the efficiency of emission is lower ($f = 1 - Q^- / Q^+ \sim 0.1$, where, $Q^+$ and $Q^-$ are the heat generation [due to viscous processes] and heat loss rates respectively. Also see, Rees [1984], where it is argued that $\dot{m} / \alpha^2$ is a good indication of the cooling efficiency of the hot flow.). We have studied a large region of parameter space in details where $0.0001 \lesssim \alpha \lesssim 1$, $0.001 \lesssim \dot{m} \lesssim 100$, $0.01 \lesssim F_{\text{Compt}} \lesssim 0.95$, $4/3 \lesssim \gamma \lesssim 5/3$ are chosen. Here, $F_{\text{Compt}}$ is the factor by which the proton temperature is reduced due to bremsstrahlung and Comptonization effects. Results with several sets of initial conditions are in MC98. Since shocks can form in advective disks for a large region of parameter space (C96 and references therein) we use
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a case with a standing shock in this paper.

In selecting the reaction network we kept in mind the fact that hotter flows may produce heavier elements through triple-$\alpha$ and rapid proton and $\alpha$ capture processes. Furthermore due to photo-dissociation significant neutrons may be produced and there is a possibility of production of neutron rich isotopes. Thus, we consider sufficient number of isotopes on either side of the stability line. The network thus contains protons, neutrons, till $^{72}Ge$ – altogether 255 nuclear species. The standard reaction rates were taken [MC98].

3. Results

We present now with a typical case which contained a shock wave in the advective region. We use the mass of the black hole $M/M_\odot = 10$, II-stress viscosity parameter $\alpha_{II} = 0.07$, the location of the inner sonic point $x_{in} = 2.9115$ and the value of the specific angular momentum at that point $\lambda_{in} = 1.6$, the polytropic index $\gamma = 4/3$ as free parameters. The net accretion rate $\dot{m} = 1$, which is the sum of (very low) Keplerian component and the sub-Keplerian component. Results of CT95 and C97a for $\dot{m}_d \sim 0.1$ and $\dot{m}_n \sim 0.9$, fix $F_{\text{Compt}} = 0.03$, $x_K = 401$. This factor is used to convert the temperature distribution of solutions of C96 (which does not explicitly uses Comptonization) to temperature distribution with Comptonization. The proton temperature and velocity distribution computed in this manner are shown in Figs. 1(a-b). (velocity is measured in units of $10^{10}$ cm sec$^{-1}$).

In Fig. 1c, we show the composition change close to the black hole both for the shock-free branch (dotted curves) and the shocked branch of the solution (solid curves). Only prominent elements are plotted. The difference between the shocked and the shock-free cases is that in the shock case the similar burning takes place farther away from the black hole because of much higher temperature in the post-shock region. A significant amount of the neutron (with a final abundance of $Y_n \sim 10^{-3}$) is produced due to photo-dissociation process. Note that closer to the black hole, $^{12}C$, $^{16}O$, $^{24}Mg$ and $^{28}Si$ are all destroyed completely, even though at around $r = 3$ or so, the abundance of some of them went up first before going down. Among the new species which are formed closer to the black hole are $^{30}Si$, $^{46}Ti$, $^{50}Cr$. Note that the final abundance of $^{20}Ne$ is significantly higher than the initial value. Thus a significant metallicity could be supplied by winds from the centrifugal barrier. In Fig. 1d, we show all the energy release/absorption components for the shocked flow. The viscous energy generation ($Q^+$) and the loss of energy ($Q_-$) from the disk (short dashed) are shown. These quantities, had the advective regime had Keplerian distribution, are also plotted (dotted). Solid curve represents the nuclear energy release/absorption for
Fig. 1: Variation of (a) proton temperature \( T_9 \), (b) radial velocity \( v_{10} \), (c) matter abundance \( Y_i \) in logarithmic scale and (d) various forms of specific energy release and absorption rates as functions of logarithmic radial distance \( x \) in units of Schwarzschild radius. See text for parameters. Solutions in the stable branch with shocks are solid curves and those without the shock are dotted in (a-c). Curves in (d) are described in the text. At the shock temperature and density rise significantly and cause a significant change in abundance even farther out. Shock induced winds may cause substantial contamination of the galactic composition when parameters are chosen from these regions.

The shocked flow and the long dashed curve is that for the shock-free flow. Dot-dashed curve represents the nuclear energy release/absorption for big-bang abundance. As matter leaves the Keplerian flow, the rapid proton capture \( (rp-) \) processes (such as, \( p + ^{18}O \rightarrow ^{15}N + ^4He \) etc.) burn hydrogen
and releases energy to the disk. At around $x = 45$, $D \rightarrow n + p$ dissociates $D$ and the endothermic reaction causes the nuclear energy release to become ‘negative’, i.e., a huge amount of energy is absorbed from the disk. At around $x = 14$ the energy release is again dominated by the original rp-processes. Excessive temperature at around $x = 12.6$ breaks $^3He$ down into deuterium This type of reactions absorb a significant amount of energy from the flow. When big-bang abundance is chosen to be the initial abundance, the net composition does not change very much, but the dominating reactions themselves are somewhat different because the initial compositions are different. For instance, in place of rapid proton capture reactions as above, the fusion of deuterium into $^4He$ plays dominant role via $D + D \rightarrow ^3He + n$, $D + p \rightarrow ^3He$, $D + D \rightarrow p + T$, $^3He + D \rightarrow p + ^4He$. This is because no heavy elements were present to begin with. Endothermic reactions at around $x = 20−40$ are dominated by deuterium dissociation as before. However, after the complete destruction of deuterium, the exothermic reaction is momentarily dominated by neutron capture processes (due to the same neutrons which are produced earlier via $D \rightarrow n + p$) such as $n + ^3He \rightarrow p + T$ which produces the spike at around $x = 14.5$. Following this, $^3He$ and $T$ are destroyed as in solar abundance case and reaches the minimum in the energy release curve at around $x = 6$. The tendency of going back to the exothermic region is stopped due to the photo-dissociation of $^4He$ via $^4He \rightarrow p + T$ and $^4He \rightarrow n + ^3He$. At the end of the big-bang abundance calculation, a significant amount of neutrons are produced. It is interesting to note that the radial dependence as well as the magnitude of the energy release due to rp-process and that due to viscous dissipation ($Q^+$) are very similar (save the region where endothermic reactions dominate). This suggests that even with nuclear reactions, at least some part of the advective disk may be perfectly stable.

We now present another interesting case where lower accretion rate ($\dot{m} = 0.01$) but higher viscosity $(0.2)$ were used and the efficiency of emission is intermediate $(f = 0.2)$. That means that the temperature of the flow is high ($F_{Compt} = 0.1$, maximum temperature $T_{9\text{max}} = 13$). $x_K = 8.4$ in this case, if the high viscosity is due to stochastic magnetic field, protons would be drifted towards the black hole due to magnetic viscosity, but the neutrons will not be drifted (Rees et al., 1982) till they decay. This principle has been used to do the simulation in this case. The modified composition in one sweep is allowed to interact with freshly accreting matter with the understanding that the accumulated neutrons do not drift radially. After few iterations or sweeps the steady distribution of the composition may be achieved. Figure 2 shows the neutron distributions in iteration numbers 1, 7, 14 & 21 respectively (from bottom to top curves) in the advective region. The formation of a ‘neutron torus’ (Hogan & Applegate, 1987) is very
Fig. 2: The convergence of the neutron abundance through successive iterations in a very hot advective disk. From bottom to top curves 1, 7, 14 and 21 iteration results are shown. A neutron torus with a significant abundance is formed in this case.

apparent in this result and generally in all the hot advective flows. Details are in Chakrabarti & Mokhopadhyay (1998).

4. Discussions and Conclusions

In this paper, we have explored the possibility of nuclear reactions in advective accretion flows around black holes. Although this region is not fully self-consistently computed yet, particularly near the region where the advective disk joins with a standard Keplerian disk, we have used the best model that is available in the literature so far (C96). Temperature in this region is controlled by the efficiencies of bremsstrahlung and Comptonization processes (CT96, C97a) and possible heating and cooling due to magnetic fields (Shapiro, 1973; Bisnovatyi-Kogan, 1998). For a higher Keplerian rate and higher viscosity, the inner edge of the Keplerian component comes closer to the black hole and the advective region becomes cooler (CT95). However, as the viscosity is decreased, the inner edge of the Keplerian component moves away and the Compton cooling becomes less efficient.

The composition changes especially in the centrifugal pressure supported denser region, where matter is hotter and slowly moving. Since centrifugal pressure supported region can be treated as an effective surface of the black hole which may generate winds and outflows in the same way
as the stellar surface, one could envisage that the winds produced in this region would carry away modified composition (Chakrabarti, 1997b; Das & Chakrabarti 1998; Das, 1998). In very hot disks, a significant amount of free neutrons are produced which, while coming out through winds may recombine with outflowing protons at a cooler environment to possibly form deuteriums a process originally suggested by Ramadurai & Rees (1985) in the context of ion tori around black holes. A few related questions have been asked lately: Can lithium in the universe be produced in black hole accretion (Jin 1990; Yi & Narayan, 1997)? We believe that this is not possible. The spallation reactions may produce such elements when only He-He reactions are considered. But when the full network is used we find that the hotter disks where spallation would have been important also photodissociate heliums to deuteriums and then to protons and neutrons before any significant lithiums could be produced. Another question is: Could the metallicity of the galaxy be explained, at least partially, by nuclear reactions? We believe that this is quite possible. Details are in MC98.

An interesting possibility of formation of the neutron torus was also discussed by Hogan & Applegate (1987): Can a neutron torus be formed around a black hole? We find that in the case of hot inflows, such formation of neutron tori is a very distinct possibility (Chakrabarti & Mukhopadhyay, 1998). Presence of a neutron torus around a black hole would help the formation of neutron rich species as well, a process hitherto attributed to the supernovae explosions only.

The advective disks as we know today do not perfectly match with a Keplerian disk. The shear, i.e., $d\Omega/dx$ is always very small in the advective flow compared to that of a Keplerian disk near the outer boundary of the advective region. We believe that such behavior is unphysical and had the viscosity $\alpha$ parameter or the cooling function were allowed to be changed continuously, such deviation would not have occurred. Thus some improvements of the disk model at the transition region is needed, but since major reactions are closer to the black hole, we believe that such modifications of the model would not change our conclusions. The neutrino luminosity is generally very large compared to the photon luminosity in case of hot disk (Mukhopadhyay & Chakrabarti 1998). In the first Case that we discussed above, neutrinos typically carry an energy of around $10^{30}$ ergs sec$^{-1}$ gm$^{-1}$. Assuming that a typical neutrino is of energy $\sim 1$ MeV, and appreciable neutrinos are emitted only from a region of a radial extent of the order of a Schwarzschild radius where the disk is also around a Schwarzschild radius thick and the density is around $10^{-9}$ gm sec$^{-1}$. In presence of hot advective disks, the number of neutrinos that should be detected per square cm area on the surface of earth would be at least a few per second provided the source is a $10M_\odot$ black hole at a distance of 10kpc. On the other hand,
neutrino luminosity from a cool advective disk is low (around $10^{15}$ ergs sec$^{-1}$ gm$^{-1}$) and no appreciable number of neutrino are expected. Thus, probably one way to check if hot, and stable advective disks exist is to look for neutrinos from the suspected black hole candidates, especially in the hard states.

In all the cases, even when the nuclear composition changes are not very significant, we note that the nuclear energy release due to exothermic reactions or absorption of energy due to endothermic reactions is of the same order as actual radiation from the disk. Unlike the gravitational energy release due to viscous processes, nuclear energy release strongly depends on temperatures. Thus, the additional energy source or sink may destabilize the flow. This aspect has not been studied in this work yet. A realistic way to do this is to include the nuclear energy also in time dependent studies of the black hole accretion (e.g., Molteni, Lanzafame & Chakrabarti, 1994; Molteni, Ryu & Chakrabarti, 1997). Such works are in progress and the results would be reported elsewhere.

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