Neutron disks around black holes

Sandip K. Chakrabarti and Banibrata Mukhopadhyay

S.N. Bose National Centre for Basic Sciences, JD Block, Salt Lake, Calcutta 700091, India

Abstract. We study nucleosynthesis in low accretion rate hot advective flows around black holes. We find that matter is generally photo-dissociated into protons and neutrons inside the disk. These neutrons stay around black holes for longer time because they are not coupled to magnetic fields while the protons accrete into the hole. We find the nature of the resulting neutron disks and estimate the rate at which these disks contaminate the surroundings.

Key words: stars: neutron – nucleosynthesis – black hole physics – accretion, accretion disks

1. Introduction

Angular momentum in accretion disks around black holes must deviate from a Keplerian distribution, since the presence of ion, radiation or inertial pressure gradient forces become as significant as the gravitational and centrifugal forces (see Chakrabarti 1996a; Chakrabarti 1996b and references therein). The inertial pressure close to a black hole is high, because, on the horizon, the inflow velocity must be equal to the velocity of light. For causality, the velocity of sound must be less than the velocity of light. In fact, in the extreme equation of state of $P = \frac{c^2}{3}\rho$ (where c is the velocity of light and P and ρ are the isotropic pressure and mass density respectively), the sound speed is only $c/\sqrt{3}$. Thus, the flow must pass through a sonic point and become supersonic before entering into the horizon. A flow which must pass through a sonic point must also be sub-Keplerian (Chakrabarti 1996b and references therein), and this causes the deviation. If the accretion rate is low, the flow cools down only by inefficient bremsstrahlung and Comptonization processes, unless the magnetic field is very high (Shvartsman 1971; Rees 1984; Bisnovatyi-Kogan 1998). This hot flow can undergo significant nucleosynthesis depending on the inflow parameters. Earlier, in the context of thick accretion disks calculations of changes in composition inside an accretion disk were carried out (Chakrabarti et al. 1987; Hogan & Applegate 1987; Arai & Hashimoto 1992; Hashimoto et al. 1993), but the disk models used were not completely self-consistent, in that neither the radial motion, nor the cooling and heating processes were in-

Send offprint requests to: S.K. Chakrabarti
(chakraba@boson.bose.res.in)

cluded fully self-consistently. Second, only high accretion rates were used. As a result, the viscosity parameter required for a significant nuclear burning was extremely low ($\alpha_{vis} < 10^{-4}$). In the present paper, we do the computation after including the radial velocity in the disk and the heating and cooling processes. We largely follow the solutions of Chakrabarti (1996b) to obtain the thermodynamic conditions along a flow.

Close to a black hole horizon, the viscous time scale is so large compared to the infall time scale that the specific angular momentum λ of matter remains almost constant and sub-Keplerian independent of viscosity (Chakrabarti 1996a,b; Chakrabarti 1989). Because of this, as matter accretes, the centrifugal force λ^2/x^3 increases much faster compared to the gravitational force GM/x^2 (where G and M are the gravitational constant and the mass of the black hole respectively, λ and x are the dimensionless angular momentum and the radial distance from the black hole). As a result, close to the black hole (at $x \sim \lambda^2/GM$) matter may even virtually stop to form standing shocks (Chakrabarti 1989). Shock or no-shock, as the flow slows down, the kinetic energy of matter is converted into thermal energy in the region where the centrifugal force dominates. Hard X-rays and γ-rays are expected from here (Chakrabarti & Titarchuk, 1995). In this centrifugal pressure supported hot 'boundary layer' (CENBOL) of the black hole (Chakrabarti et al. 1996) we find that for low accretion rates, ^4He of the infalling matter is completely photo-dissociated and no ^7Li could be produced. In this region, about ten to twelve percent of matter is found to be made up of pure neutrons. These neutrons should not accrete very fast because of very low magnetic viscosity associated with neutral particles (Rees et al. 1982) while protons are dragged towards the central black hole along with the field lines. Of course, both the neutrons and protons would have 'normal' ionic viscosity, and some slow accretion of protons (including those produced after neutron decay) would still be possible. In contrast to neutron stars, the *neutron disks* which we find are not dense. Nevertheless, they can participate in the formation of neutron rich isotopes and some amount of deuterium. They can be eventually dispersed into the galaxy through jets and outflows, which come out of CENBOL (Chakrabarti 1998; Das & Chakrabarti 1998) thereby possibly influencing the metallicity of the galaxy.

On the equatorial plane, where the viscosity is the highest, a Keplerian disk deviates to become sub-Keplerian *very close*

to the black hole (Chakrabarti & Titarchuk 1995; Wiita 1982). Away from the equatorial plane, viscosity is lower and the flow deviates from a Keplerian disk farther out. This is because the angular momentum transport is achieved by viscous stresses. Weaker the viscosity, longer is the distance through which angular momentum goes to match with a Keplerian disk. When the viscosity of the disk is decreased on the whole, the Keplerian disk recedes from the black hole forming quiescence states when the objects become very faint in X-rays (Ebisawa et al. 1996). Soft photons from the Keplerian disk are intercepted by this sub-Keplerian boundary layer (CENBOL) and photons are energized through Compton scattering process. For higher Keplerian rates, electrons and protons cool down completely and the black hole is in a *soft state* (Tanaka & Lewin 1995). Here, bulk motion Comptonization produces the power-law tail of slope $\alpha \sim 1.5$ (Chakrabarti & Titarchuk 1995; Titarchuk et al. 1997). For lower Keplerian rates, the Compton cooling is incomplete and the temperature of the boundary layer remains close to the virial value,

$$T_p \sim \frac{1}{2k} m_p c^2 \frac{x_g}{x} = 5.2 \times 10^{11} \left(\frac{10}{x/x_g} \right) \quad ^{\circ}\text{K}. \tag{1}$$

In this case, bremsstrahlung is also important and the black hole is said to be in a *hard state* with energy spectral index α ($F_\nu \sim \nu^{-\alpha}$, where ν is the frequency of the photon) close to 0.5. In Eq. (1), m_p is the mass of the proton, $x_g = 2GM/c^2$ is the Schwarzschild radius of the black hole, and c is the velocity of light. (In future, we measure the distances and velocities in units of x_g and c.) In this low Keplerian rate, electrons are cooler typically by a factor of $(m_p/m_e)^{1/2}$ unless the magnetic field is very high. Present high energy observations seem to support the apparently intriguing aspects of black hole accretion mentioned above. For instance, the constancy of (separate) spectral slopes in soft and hard states has been observed by many (Ebisawa et al. 1994; Miyamoto et al. 1991; Ramos et al. 1997; Grove et al. 1998; Vargas et al. 1997). ASCA observations of Cygnus X-1 seem to indicate that the inner edge of the Keplerian component is located at around $15R_g$ (instead of $3R_g$) (Gilfanov et al. 1997). HST FOS observations of the black hole candidate A0620-00 in quiescent state seems to have very faint Keplerian features (McClintock et al. 1995) indicating the Keplerian component to be farther out at low accretion rates. Bulk motion Comptonization close to the horizon has been considered to be a possible cause of the power-law tail in very soft states (Crary et al. 1996; Ling et al. 1997; Cui et al. 1997). However, some alternative modes may not be ruled out to explain some of these features.

This observed and predicted dichotomy of states of black hole spectra motivated us to investigate the nuclear reactions thoroughly for both the states, but we report here the results obtained in the more important case, namely, when the flow is hotter, i.e., for hard states. We use 255 nuclear elements in the thermo-nuclear network starting from protons, neutrons, deuterium etc. till ^{72}Ge and the nuclear reaction rates valid for high temperatures. We assume that accretion on the galactic black hole is taking place from a disk where matter is supplied

from a normal main sequence star. That is, we choose the abundance of the injected matter to be that of the sun. Because of very high temperature, the result is nearly independent of the initial composition, as long as reasonable choices are made. When accretion rates are higher, the advective region becomes cooler and very little nucleosynthesis takes place, the results are presented elsewhere (Mukhopadhyay 1998; Mukhopadhyay & Chakrabarti 1998).

As hot matter approaches a black hole, photons originated by the bremsstrahlung process, as well as those intercepted from the Keplerian disk, start to photo-dissociate deuterium and helium in the advective region. There are two challenging issues at this stage which we address first: (a) Thermodynamic quantities such as density and temperature inside a disk are computed using a *thin disk* approximation, i.e., the vertical height $h(x)$ at a radial distance x very small compared to x ($h(x) << x$), and assuming the flow to be instantaneously in vertical equilibrium. However, at a low rate, it is easy to show that the disk is optically thin in the vertical direction $\int_0^{h(x)} \rho\sigma dh < 1$ (σ is the Thomson scattering cross-section). However, soft photons from the Keplerian disk enter radially and $\int_1^{x_s} \rho\sigma dx > 1$, generally. In fact, this latter possibility changes the soft photons of a few keV from a Keplerian disk to energies up to $\sim 1\text{MeV}$ by repeated Compton scattering (Sunyaev & Titarchuk 1980; Chakrabarti & Titarchuk 1995) while keeping the photon number strictly constant. The spectrum of the resultant photons emitted to distant observers becomes a power law $F_\nu \sim \nu^{-\alpha}$ instead of a blackbody, where $\alpha \sim 0.5$ for hard state and $\alpha \sim 1.5$ for soft states of a black hole. (b) Now that the spectrum is not a blackbody, strictly speaking, the computation of photo-disintegration rate that is standard in the literature (which utilizes a Planckian spectrum) cannot be followed. Fortunately, this may not pose a major problem. As we shall show, the standard photo-disintegration rate yields a lower limit of the actual rate that takes place in the presence of power-law photon spectra. Thus, usage of the correct rate obtainable from a power-law spectrum would, if anything, strengthen our assertion about the photo-disintegration around a black hole. After photo-disintegration by these hard photons, all that are left are protons and neutrons. The exact location where the dissociation actually starts may depend on the detailed photon spectrum, i.e., optical depth of this boundary layer and the electron temperature.

The plan of the present paper is the following: in the next section, we present briefly the hydrodynamical model using which the thermodynamic quantities such as the density and temperature inside the inner accretion disk are computed. We also present the model parameters we employ. In Sect. 3, we present results of nucleosynthesis inside a disk. Finally, in Sect. 4, we present out concluding remarks.

2. Model determining the thermodynamic conditions

We chose the units of distance, time and mass to be $2GM/c^2$, $2GM/c^3$ and M where, G is the gravitational constant, M is the mass of the black hole, and c is the velocity of light. To keep the problem tractable without sacrificing the salient features,

we use a well understood model of the accretion flow close to the black hole. We solve the following equations (Chakrabarti 1996a,b) to obtain the thermodynamic quantities:

(a) The radial momentum equation:

$$\vartheta \frac{d\vartheta}{dx} + \frac{1}{\rho}\frac{dP}{dx} + \frac{\lambda_{Kep}^2 - \lambda^2}{x^3} = 0, \tag{2a}$$

(b) The continuity equation:

$$\frac{d}{dx}(\Sigma x \vartheta) = 0, \tag{2b}$$

(c) The azimuthal momentum equation:

$$\vartheta \frac{d\lambda(x)}{dx} - \frac{1}{\Sigma x}\frac{d}{dx}(x^2 W_{x\phi}) = 0, \tag{2c}$$

(d) The entropy equation:

$$\begin{aligned}
\Sigma v T \frac{ds}{dx} &= \frac{h(x)\vartheta}{\Gamma_3 - 1}\left(\frac{dp}{dx} - \Gamma_1 \frac{p}{\rho}\right) \\
&= Q_{mag}^+ + Q_{nuc}^+ + Q_{vis}^+ - Q^- \\
&= Q^+ - g(x,\dot{m})Q^+ = f(\alpha, x, \dot{m})Q^+.
\end{aligned} \tag{2d}$$

Here, Q^+ and Q^- are the heat gained and lost by the flow, and $\dot{m}$ is the mass accretion rate in units of the Eddington rate. Here, we have included the possibility of magnetic heating Q_{mag}^+ (due to stochastic fields; Shvartsman 1971; Shapiro, 1973; Bisnovatyi-Kogan, 1998) and nuclear energy release Q_{nuc}^+ as well (cf. Taam & Fryxall 1985) while the cooling is provided by bremsstrahlung, Comptonization, and endothermic reactions and neutrino emissions. A strong magnetic heating might equalize ion and electron temperatures (e.g. Bisnovatyi-Kogan 1998) but this would not affect our conclusions. On the right hand side, we wrote Q^+ collectively proportional to the cooling term for simplicity (purely on dimensional grounds). We use the standard definitions of Γ (Cox & Giuli 1968),

$$\Gamma_3 = 1 + \frac{\Gamma_1 - \beta}{4 - 3\beta},$$

$$\Gamma_1 = \beta + \frac{(4 - 3\beta)^2(\gamma - 1)}{\beta + 12(\gamma - 1)(1 - \beta)}$$

and $\beta(x)$ is the ratio of gas pressure to total pressure,

$$\beta(x) = \frac{\rho k T/\mu m_p}{\rho k T/\mu m_p + \bar{a}T^4/3 + B(x)^2/4\pi}$$

Here, $\bar{a}$ is the Stefan constant, k is the Boltzman constant, m_p is the mass of the proton, μ is the mean molecular weight. Using the above definitions, Eq. (2d) becomes,

$$\frac{4 - 3\beta}{\Gamma_1 - \beta}\left[\frac{1}{T}\frac{dT}{dx} - \frac{1}{\beta}\frac{d\beta}{dx} - \frac{\Gamma_1 - 1}{\rho}\frac{d\rho}{dx}\right] = f(\alpha, x, \dot{m})Q^+. \tag{2e}$$

In this paper, we shall concentrate on solutions with constant β. Actually, we study in detail only the special cases, $\beta = 0$ and $\beta = 1$, so we shall liberally use $\Gamma_1 = \gamma = \Gamma_3$. We note here that unlike *self-gravitating* stars where $\beta = 0$ causes instability, here this is not a problem. Similarly, we shall consider the case

for $f(\alpha, x, \dot{m}) = $ constant, though as is clear, $f \sim 0$ in the Keplerian disk region and probably much greater than 0 near the black hole depending on the efficiency of cooling (governed by $\dot{m}$, for instance). We use the Paczyński-Wiita (1980) potential to describe the black hole geometry. Thus, λ_{Kep}, the Keplerian angular momentum is given by, $\lambda_{Kep}^2 = x^3/2(x - 1)^2$, exactly same as in general relativity. $W_{x\phi}$ is the vertically integrated viscous stress, $h(x)$ is the half-thickness of the disk at radial distance x (both measured in units of $2GM/c^2$) obtained from vertical equilibrium assumption (Chakrabarti 1989) $\lambda(x)$ is the specific angular momentum, ϑ is the radial velocity, s is the entropy density of the flow. The constant α above is the Shakura-Sunyaev (1973) viscosity parameter modified to include the pressure due to radial motion ($\Pi = W + \Sigma\vartheta^2$, where W and Σ are the integrated pressure and density respectively; see Chakrabarti & Molteni (1995) in the viscous stress. With this choice, $W_{x\phi}$ keeps the specific angular momentum continuous across of the shock.

For a complete run, we supply the basic parameters, namely, the location of the sonic point through which flow must pass just outside the horizon X_{out}, the specific angular momentum at the inner edge of the flow λ_{in}, the polytropic index γ, the ratio f of advected heat flux $Q_+ - Q_-$ to heat generation rate Q^+, the viscosity parameter α_{vis} and the accretion rate $\dot{m}$. The derived quantities are: x_{tr} where the Keplerian flow deviates to become sub-Keplerian, the ion temperature T_p, the flow density ρ, the radial velocity v_r and the azimuthal velocity λ/x of the entire flow from x_{tr} to the horizon. Temperature of the ions obtained from above equations is further corrected using a cooling factor F_{Comp} obtained from the results of radiative transfer of Chakrabarti & Titarchuk (1995). Electrons cool due to Comptonization, but they cause the ion cooling also since ions and electrons are coupled by Coulomb interaction. F_{Comp}, chosen here to be constant in the advective region, is the ratio of the ion temperature computed from hydrodynamic (Chakrabarti 1996b) and radiation-hydrodynamic (Chakrabarti & Titarchuk 1995) considerations.

3. Results of nucleosynthesis calculations

In the first example, we start with a relativistic flow (polytropic index $\gamma = 4/3$) with the accretion rate $\dot{M} = 0.01\dot{M}_{Edd}$, where, $\dot{M}_{Edd}$ is the Eddington accretion rate. We use the mass of the central black hole to be $M = 10M_\odot$ throughout. We choose a very high viscosity and the corresponding α parameter (Shakura & Sunyaev 1973) is 0.2 in the sub-Keplerian regime. The cooling is not as efficient as in a Keplerian disk: $Q^- \sim 0.9Q^+$, where, Q^+ and Q^- are the heat generation and heat loss rates respectively. The specific angular momentum at the inner edge is $\lambda_{in} = 1.65$ (in units of $2GM/c$). The flow deviates from a Keplerian disk at 4.15 Schwarzschild radii. It is to be noted that Q^- includes *all possible* types of cooling, such as bremsstrahlung, Comptonization as well as cooling due to neutrino emissions. We assume that the flow is magnetized so that only ions have larger viscosity. Due to poor supply of the soft photons from Keplerian disks, the Comptonization in the boundary layer is
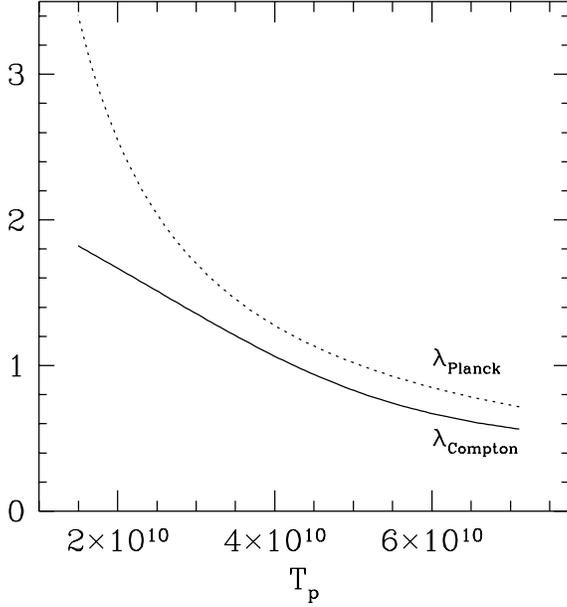
Fig. 1. Comparison of wavelength λ_{Planck} at peak blackbody intensity (dotted) with the mean (taken between 2 and 50 keV) wavelength of the Comptonized power law spectrum (solid) of the emitted X-rays. Wavelengths are measured in units of 10^{-11} cm.

not complete: we assume a standard value (Chakrabarti, & Titarchuk 1995) in this regime: $F_{Comp} \sim 0.1$, i.e., ions (in te radiation-hydrodynamic solution) are one-tenth as hot as obtained from the hydrodynamic solutions. [For high accretion rate, $\dot{m} \gtrsim 0.3$, $F_{Comp} \sim 0.001$ and ions and electrons both cool to a few KeV ($\sim 10^7$ °K)]. The typical density and temperature near the marginally stable orbit are $\rho_{x=3} \sim 8.5 \times 10^{-8}$ gm cm^{-3} and 7.5×10^9 °K respectively where the thermonuclear depletion rates $N_A < \sigma v >$ for the $D \rightarrow p + n$, $^4He \rightarrow D + D$ and $^4He +^4 He =^7 Li + p$ reactions are given by 1.6×10^{14} gm^{-1} s^{-1}, 4×10^{-3} gm^{-1} s^{-1} and 1.9×10^{-12} gm^{-1} s^{-1} respectively. Here, N_A is the element abundance on the left, σ is the reaction cross-section, v is the Maxwellian average velocity of the reactants. At these rates, the time scales of these reactions are given by, 4×10^5 s, 5×10^{11} s and 4×10^{20} s respectively indicating that the deuterium burning is the fastest of the reactions. In fact, it would take about a second to burn initial deuterium with $Y_D = 10^{-5}$. The ^7Li does not form at all because the ^4He dissociates to D much faster.

The above depletion rates have been computed assuming Planckian photon distribution corresponding to ion temperature T_p. The wavelength λ_{Planck} at which the brightness is highest at $T = T_p$ is shown in Fig. 1 in the dashed curve (in units of 10^{-11} cm). Also shown is the *average* wavelength of the photon $\lambda_{Compton}$ (solid curve) obtained from the spectrum $F_\nu \sim \nu^{-\alpha}$. The average has been performed over the region 2 to 50 keV of the photon energy in which the hard component is usually observed

$$\langle F_\nu \rangle = \frac{\int_{\nu_{min}}^{\nu_{max}} F_\nu d\nu}{\int_{\nu_{min}}^{\nu_{max}} d\nu} = \nu_{Compton}^{-\alpha} \qquad (3)$$
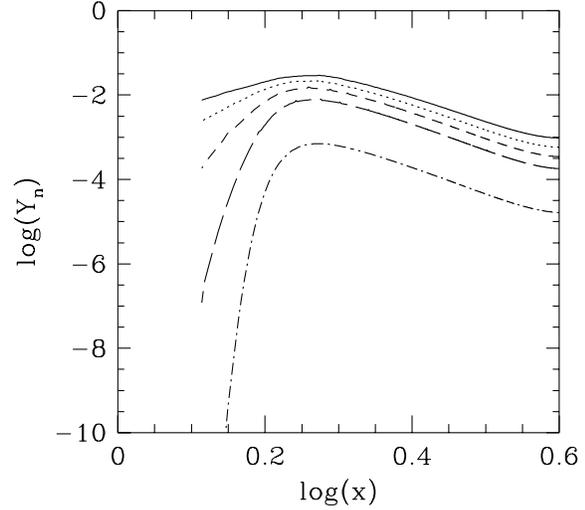

Fig. 2. Formation of a steady *neutron torus* in a hot inflow. Intermediate iteration results (from bottom to top: 1st, 11th, 21st, 31st and 41st iterations respectively) of the logarithmic neutron abundance Y_n in the flow as a function of the logarithmic radial distance (x in units of Schwarzschild radius) are shown.

where, ν_{min} and ν_{max} are computed from 2 and 50 keV respectively. The average becomes a function of the energy spectral index α ($F_\nu \propto \nu^{-\alpha}$), which in turn depends on the ion and electron temperatures of the medium. We follow Chakrabarti & Titarchuk (1995) to compute these relations. We note that $\lambda_{Compton}$ is *lower* compared to λ_{Planck} for all ion temperatures we are interested in. Thus, the disintegration rate with Planckian distribution that we employed in this paper is clearly a lower limit. Our assertion of the formation of a neutron disk should be strengthened when Comptonization is included.

Fig. 2 shows the result of the numerical simulation for the disk model mentioned above. Logarithmic abundance of neutron Y_n is plotted against the logarithmic distance from the black hole. First simulation produced the dash-dotted curve for the neutron distribution, forming a miniature neutron torus. As fresh matter is added to the existing neutron disk, neutron abundance is increased as neutrons do not fall in rapidly. Thus the simulation is repeated several times in order to achieve a converging steady pattern of the neutron disk. Although fresh neutrons are deposited, the stability of the distribution is achieved through neutron decay and neutron capture reactions. Results after every ten iterations are plotted. The equilibrium neutron torus remains around the black hole indefinitely. The neutron abundance is clearly very significant (more than five per cent!).

We study yet another case where the accretion rate is smaller ($\dot{m} = 0.001$) and the viscosity is so small ($\alpha = 0.01$) and the disk so hot that the sub-Keplerian flow deviates from a Keplerian disk farther away at $x = 85.1$. The polytropic index is that of a mono-atomic (ionized) hot gas $\gamma = 5/3$. The Compton cooling factor is as above since it is independent of the accretion rates as long as the rate is low (Sunyaev & Titarchuk 1980; Chakrabarti & Titarchuk 1995). The cooling is assumed to be very inefficient because of lower density: $Q^- \sim 0.4 Q^+$.
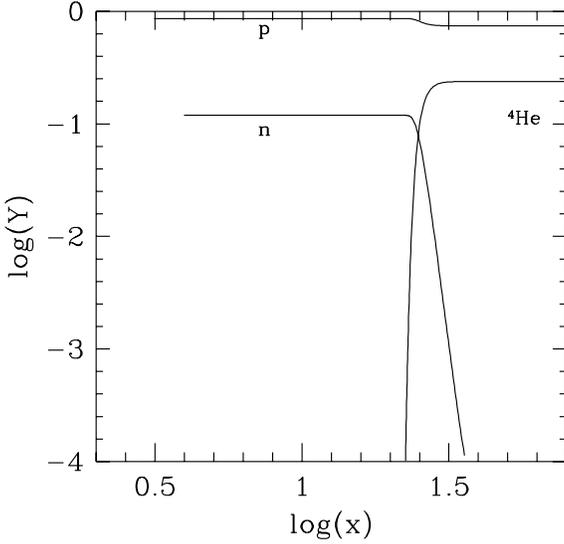
Fig. 3. Variation of matter abundance Y_i in logarithmic scale in a hot flow around a galactic black hole. Entire ^4He is photodissociated at around $x = 30x_g$ and the steady neutron disk is produced for $x < 30$ which is not accreted.

The specific angular momentum at the inner edge of the disk is $\lambda_{in} = 1.55$. In Fig. 3, we show the logarithmic abundances of proton (p), helium (^4He) and neutron (n) as functions of the logarithmic distance from the black hole. Note that ^4He dissociates completely at a distance of around $x = 30$ where the density and temperatures are $\rho = 2.29 \times 10^{-11}$ gm cm^{-3} and $T = 6.3 \times 10^9$ ^oK. Maximum temperature attained in this case is $T_{max} = 3.7 \times 10^{10}$ ^oK. Both the neutrons and protons are enhanced for $x \lesssim 30$, the boundary layer of the black hole. This neutron disk also remains stable despite neutron decay, since new matter moves in to maintain equilibrium. The ^7Li abundance is insignificant.

4. Concluding remarks

In this paper, we have shown that hot flows may produce neutron disks around black holes, where neutron abundance is significant. However, unlike neutron stars, the formation of which is accompanied by the production of neutron rich isotopes, neutron disks do not produce significant neutron rich elements. Some fragile elements, such as deuterium, could be produced in the cooler outflows as follows:

Neutrons and protons may be released in space through winds which are produced in the centrifugal barrier. These winds are common in black hole sources and earlier they have been attributed to the dispersal of magnetic fields to the galactic medium (Daly & Loeb 1990; Chakrabarti et al. 1994). Recently, Chakrabarti (1998) and Das & Chakrabarti (1998), through a first ever self-consistent calculation of outflows out of accretion, found that significant winds can be produced and for low enough accretion rates, disks may even be almost evacuated causing the formation of quiescence and inactive states such as what is observed in V404 Cyg and our Galactic centre. If the

temperature of the wind falls off as $1/z$ and density as $z^{-3/2}$ (as is expected from an outflow of insignificant rotation), the deuterium synthesis rate $n + p \to D$, increases much faster very rapidly than the reverse ($D \to n + p$) process. For instance, with density and temperature mentioned as in the earlier section, at $z = 30x_g$, the forward rate ($N_A < \sigma v >$) is 0.12×10^{-5} while the reverse rate is much higher: 6.7×10^{13}. This results in the dissociation of deuterium. However, at $z = 300x_g$, the above rates are 1.8×10^{-8} and 9.6×10^{-6} respectively and at $z = 3000x_g$, the above rates are 1.3×10^{-8} and $\sim 10^{-165}$ respectively. Thus a significant deuterium could be produced farther out, say, starting from a distance of $\sim 10^3 x_g$. Ramadurai & Rees (1985) suggested deuterium formation on the surface of ion tori. As we establish here, this process may be feasible, only if these tori are vertically *very thick*: $z(x) \sim 10^3 x_g$. In any case, deuterium would be expected to form in winds and disperse.

In a typical case of a disk with an accretion rate of $\dot{M} \sim \dot{M}_{Edd}$, the temperature is lower, but the density is higher. In that case, the photo-dissociation of ^4He is insignificant and typically the change in abundances of some of the elements, such as ^{16}O, ^{20}Ne etc. could be around $\Delta Y \sim 10^{-3}$ not as high as that of the neutron as in above cases where $\Delta Y_n \sim 0.1$. One could estimate the contamination of the galactic metalicity due to nuclear reactions as we do for realistic models. Assume that, on an average, all the N stellar black holes of equal mass M have a non-dimensional accretion rate of around $\dot{m} \sim 1$ ($\dot{m} = \dot{M}/\dot{M}_{Edd}$). Let ΔY_i be the typical change in composition of this matter during the run and let f_w be the fraction of the incoming flow that goes out as winds and outflows, then in the lifetime of a galaxy (say, 10^{10} yrs), the total 'change' in abundance of a particular species deposited to the surroundings by all the stellar black holes is given by:

$$\langle \Delta Y_i \rangle \cong 10^{-9} \left(\frac{\dot{m}}{1} \right) \left(\frac{N}{10^6} \right) \left(\frac{\Delta Y_i}{10^{-3}} \right) \left(\frac{f_w}{0.1} \right) \left(\frac{M}{10 M_\odot} \right)$$
$$\times \left(\frac{T_{gal}}{10^{10}} \right) \left(\frac{M_{gal}}{10^{13} M_\odot} \right)^{-1}. \qquad (4)$$

We here assume a conservative estimate that there are 10^6 such stellar black holes (there number varies from 10^8 (van den Heuvel 1992, 1998) to several thousands (Romani, 1998) depending on assumptions made) and the mass of the host galaxy is around $10^{13} M_\odot$ and the lifetime of the galaxy during which such reactions are going on is about 10^{10}Yrs. We believe that $< \Delta Y_i > \sim 10^{-9}$ is quite reasonable for a typical case when $\Delta Y_i \sim 10^{-3}$ and a fraction of ten percent of matter is blown off as winds. When $\Delta Y_i \sim 0.1$ or the outflow rate is higher (particularly in presence of strong centrifugal barrier) the contamination would be even higher.

It is to be noted that our assertion of formation of neutron disks around a black hole for very low accretion rate $\dot{M} \sim 0.001$–$0.01\dot{M}_{Edd}$ is different from that of the earlier results (Hogan & Applegate 1987) where $\dot{M} \sim 10\dot{M}_{Edd}$ was believed to be the more favourable accretion rate. This is because in last decades the emphasis was on super-Eddington thick accretion

tori. More recent computations suggest that advective regions are not as hot when the rates are very high. Another assertion of our work is that ^7Li should not be produced in accretion disks at all. This is not in line with earlier suggestions (Jin 1990) also. That is because unlike earlier case where the spallation reaction $^4He + ^4He$ was dealt with in isolation, we study this in relation to other reactions prevalent in the disk. We find that ^4He could be dissociated much before it can contribute to spallation. However, our work supports Ramadurai & Rees' (1985) conjecture that deuterium may be produced in the outer regions of the disk provided the disk is at least as thick as $10^3 x_g$.

In the process of performing the simulation we were faced with a challenge which was never addressed earlier in the literature. The problem arises because the inflow under consideration is optically thin vertically, but optically thick horizontally. As a result, photons emitted form a power-law spectrum. Question naturally arises, whether these power-law photons are capable of photo-disintegration. We find that the answer is yes and that the calculation of usual photo-disintegration gives a lower limit of the changes in the composition. In the extreme conditions close to the black hole, such processes are sufficiently effective to produce neutron disks around black holes.

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