Chapter 5

Accretion column emission in EXO 2030+375: a physical perspective

The study of spectral properties of EXO 2030+375 by using empirical model such as high-energy cutoff power-law model over a broad range of the pulsar luminosity, during Type I and Type II X-ray outbursts has enriched our understanding about beamed emission of the pulsar. A thorough and detailed spectral investigation of RXTE pointed observations of EXO 2030+375 carried out at different luminosities during different types of outbursts in a time span of over a decade showed that, depending on source luminosity, the power-law photon index was distributed in three distinct regions. It suggests the phases of spectral transition from sub-critical to super-critical regimes in the pulsar. A region with constant photon index was also observed in $\sim (2 - 4) \times 10^{37}$ erg s$^{-1}$ range, indicating critical luminosity regime in EXO 2030+375. The existence of this regime is also reflected in the pulse profile variations with luminosity as the emission geometry probably changed from a pure pencil beam emission at lower X-ray luminosity to a mixture of pencil and fan beam emission at critical luminosity. Despite our understanding of structural changes in column emission of the pulsar, we are still clueless of the physical properties of accretion column. The empirical models could not address fully the complex emission processes happening near the pulsar site which shape the accretion
column. In order to comprehend the dynamics of radiative processes happening at these sites which also possess strong magnetic field ($\sim 10^{12} G$), a proper physical model accounting for all the source properties should be considered. In the present Chapter, we explore the accretion column emission properties of the BeXB pulsar EXO 2030+375. For the first time we have used a physical model (BW model, Becker and Wolff 2007; Ferrigno et al. 2009) to describe the continuum spectrum of EXO 2030+375. This model is based on thermal & bulk Comptonization of infalling plasma in the accretion column. It could describe the physical properties of accretion column across wide range of the pulsar luminosity.

### 5.1 Physical Spectral Model

The X-ray continuum spectra of accretion powered pulsars is a result of complex physical phenomena happening at the vicinity of pulsar accretion column. The incoming plasma entrained by the dense magnetic field into narrow regions of pulsar accretion column decelerates through a radiative shock before settling onto the neutron star surface. The deceleration causes the gas to fall at relativistic speed. This in turn causes the accreting matter to lose its enormous gravitational energy through emitting X-ray photons from the regions around the accretion column. The X-ray luminosity of accretion powered pulsars ranges in $L_x \sim 10^{34} - 10^{38}$ erg s$^{-1}$ with the pulse periods varying in $0.1 \, s \leq P_{\text{spin}} \leq 1000 \, s$. The resulting spectra of the pulsars are often fitted with various forms of power-law and sometimes with the combination of a blackbody component (with temperature, $T \sim 10^6 - 10^7 \, K$). In few of these sources, signatures of cyclotron line features in 10-100 keV range spectra are also seen apart from iron emission lines. Despite the fact that the broad-band X-ray spectra of accretion powered pulsars enrich with occasional emission or absorption features, there is no convincing physical model which could explain all the observed spectral components. There have been several attempts to calculate the spectra of these pulsars by considering the radiative processes happening at the accretion column. Recent developments in understanding the spectral formation in accretion powered pulsars has lead to many physical models which can explain the observed
5.1 Physical Spectral Model

spectra. Among these the promising one is the thermal & bulk Comptonization model proposed by Becker and Wolff (2007). This model has been used in our spectral investigation of RXTE observations of EXO 2030+375 to estimate the characteristic parameters of the pulsar. This has been discussed below.

5.1.1 Thermal and Bulk Comptonization model

Radiative processes such as blackbody, Comptonization etc. play a major role in broad-band X-ray emission from accretion powered binary pulsars. The Comptonization process is also the primary mode of interaction between photons and electrons present in a radiation dominated plasma such as in accretion column. In order to explain the high energy spectrum comprising column emission from X-ray pulsars, Becker and Wolff (2007) developed a physical model based on ‘bulk’ and ‘thermal’ Comptonization of seed photons in the accretion column. The seed photons in turn were produced from the bremsstrahlung and cyclotron emission in the accretion column and from the blackbody emission emerging from thermal mound located near the neutron star surface. As the seed photons diffuse through the accretion column, they are scattered by infalling high speed electrons in the accreting plasma. The plasma settles onto the neutron star surface as the photons escaping through the column wall carry away the kinetic energy of the infalling gas. In the “pure” bulk Comptonization process, the seed photons gain energy as they collide with the rapidly compressing gas in the accretion column. The Comptonization process results in a mean energy gain by the seed photons as they collide with the scattering centers (i.e infalling electrons) within the accretion column. However, in thermal Comptonization, the seed photons are energized by ‘stochastic’ motions of electrons produced by second-order Fermi mechanism (Becker, 2003; Sunyaev and Titarchuk, 1980).

The Becker & Wolff (BW) model as proposed by Becker and Wolff (2007), consists of free parameters such as column radius ($r_0$), gas temperature in the thermal mound ($T_{th}$), electron temperature in the optically thin region above the thermal mound ($T_e$), strength of magnetic field ($B$) and mass accretion rate ($\dot{M}$). The number of free parameters gets reduced with additional constraints relating these
Fig. 5.1 Schematic representation of matter accretion onto the pole of a neutron star as depicted in Becker and Wolff (2007). A radiation dominated shock is formed above the neutron star surface before the accreting gas settles onto the neutron star surface. The dense thermal mound located inside the accretion column just above the surface is the source of most of the photons emitted from the column. The blackbody photons originated in the thermal mound are eventually up-scattered in the shock and diffuse through the column walls. The settling of the thermal plasma onto the stellar surface is possible as the escaping photons carry away the kinetic energy of the gas.

parameters. In case of accretion powered X-ray pulsars, if we consider standard values of neutron star mass and radii as $M_{NS} = 1.4 \, M_{\odot}$ and $R_{NS} = 10 \, km$, respectively, then there are only 6 free parameters that need to be varied while fitting the broad-band spectrum. These are namely, $T_e, \dot{M}, r_0, B, \delta$ and $\xi$. Last two parameters such as the Comptonization parameter, $\delta$ and the photon diffusion parameter, $\xi$ are defined as:

$$\xi \equiv \frac{\pi r_0 m_p c}{M \sqrt{\sigma_\perp \sigma_\parallel}}$$  \hspace{1cm} (5.1)

$$\frac{\delta}{4} = \frac{\gamma_{\text{bulk}}}{\gamma_{\text{thermal}}}$$  \hspace{1cm} (5.2)

Here, $m_p$ denotes the proton mass, $c$ is the speed of light and $\sigma_\perp$ & $\sigma_\parallel$ are respectively the energy averaged scattering cross-sections of photons propagating
perpendicular and parallel to the magnetic field. The \( \gamma_{\text{bulk}} \) and \( \gamma_{\text{thermal}} \) represent the Compton \( \gamma \) parameters due to bulk and thermal Comptonization processes. The diffusion parameter \( \delta \) subsequently signifies the leading Comptonization process in energizing the photons that are escaping from the accretion column as emerging X-ray radiation. For values of \( \delta \gg 1 \), the bulk Comptonization plays a major role in photon energization and for \( \delta \ll 1 \), the thermal Comptonization leads in energization of the escaping photons. At the values of diffusion parameter, i.e. \( \delta \sim 1 \), the energy transfer between electrons and photons is equally led by the two Comptonization processes (Becker and Wolff, 2007).

### 5.1.2 BW model explaining the spectra of EXO 2030+375

To explore the physical properties of accretion column, we have fitted the Becker & Wolff (BW) model with the phase averaged spectra of EXO 2030+375 in wide luminosity range \((i.e. 10^{36} \lesssim L_x \lesssim 10^{38} \text{ erg s}^{-1})\). This model is proposed by Becker and Wolff (2007) to explain the emission from accretion powered X-ray pulsars by considering the effects of thermal and bulk Comptonization in accretion column. It has been successful in explaining the broadband spectra of bright X-ray pulsars such as 4U 0115+63 (Ferrigno et al., 2009), 4U 1626-67 (D’Ai et al., 2017), Her X-1 (Wolff et al., 2016). According to this model, seed photons originated due to bremsstrahlung, blackbody and/or cyclotron emissions undergo thermal and bulk Comptonization in the accretion column. Comptonization of these seed photons with highly energetic electrons lead to the power-law like resultant spectrum with high energy exponential cutoff.

Using this model, we have described the 3-70 keV broad-band phase-averaged spectra of EXO 2030+375 at 23 different luminosity epochs, covering the range of \( 10^{36} - 10^{38} \text{ erg s}^{-1} \). As mentioned above, for a canonical neutron star mass and radius, the BW model has six free parameters, i.e. the diffusion parameter \( \xi \), the ratio of bulk to thermal Comptonization \( \delta \), the column radius \( r_0 \), mass accretion rate \( \dot{M} \), electron temperature \( T_e \) and the magnetic field strength \( B \). Among these parameters, the mass accretion rate \( \dot{M} \) was estimated by using the observed source flux obtained from high energy cutoff empirical model and considering a source distance of 7.1 kpc.
Table 5.1 Best-fitting spectral parameters with 1σ errors obtained from XTEJ1795+058 observations of EXO 2030+375 with BW model.

<table>
<thead>
<tr>
<th>Source</th>
<th>(m)</th>
<th>(E)</th>
<th>(\chi^2)</th>
<th>(S_{\text{X}})</th>
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Notes: The 3-70 keV luminosity in the units of 10^{35} erg/s, assuming a distance of 7.1 kpc.

‡: Indicates the observation IDs from which the extracted spectra are shown in the Figure 5.2.
Fig. 5.2 Phase-averaged energy spectra of EXO 2030+375 at three distinct luminosities obtained during Type I and Type II X-ray outbursts obtained from PCA and HEXTE detectors. The spectra of pulsar was fitted with BW model (Ferrigno et al., 2009) along with an iron line at \( \sim 6.4 \) keV and partial covering component (top panel of figure). Corresponding spectral residuals are shown in bottom panels of the figure. Presence of any absorption like feature was not seen in 10–20 keV energy range of the pulsar spectra.
(Wilson et al., 2002). Since the column radius strongly depends on accretion rate (see Eqn. 112 of Becker and Wolff 2007), the parameter $\dot{M}$ was fixed at a given value while fitting the broad-band spectrum of the pulsar. After fitting, the column radius was also fixed for getting better constraints on other spectral parameters. This was done carefully by analyzing the 2-D contour plots between $r_0$ & $\dot{M}$, as done by Ferrigno et al. (2009). Other BW model components such as normalizations of Bremsstrahlung, cyclotron and blackbody seed photons were also kept fixed as suggested in the BW_cookbook1.

A partial covering component as required in empirical models was also needed to explain the absorbed spectra of the pulsars during bright X-ray outbursts. The values of additional column density and covering fraction obtained from the BW model were found to be consistent with the values obtained with the high energy cutoff power-law model (see Table 4.2 of Chapter 4). Therefore, we have not discussed these parameters in this section. An iron fluorescence line at $\sim$ 6.4 keV was also added in the continuum. Spectral parameters obtained after best fitting the pulsar spectra with BW model are given in Table 5.1. The values of reduced $\chi^2$ obtained from our fitting, as given in Table 5.1, showed that the BW continuum model fits the data well in a wide luminosity range. For three different values of pulsar luminosity, broadband energy spectra of the pulsar from PCA and HEXTE detectors, along with the best-fitted BW continuum model and Gaussian function for iron emission line are presented in top panels of the Figure 5.2. The bottom panels in this figure show corresponding spectral residuals of best fitted model. It can be seen that the residuals obtained from fitting the pulsar spectra with BW model did not show any evidence of presence of absorption like feature. This finding also supports the non-detection of cyclotron line in EXO 2030+375, as discussed in Section 4.3 of Chapter 4. Luminosity dependent variations in the parameters obtained after fitting the pulsar spectra with BW model are shown in Figure 5.3.

1http://www.isdc.unige.ch/~ferrigno/images/Documents/BW_distribution/BW_cookbook.html
Fig. 5.3 Spectral parameters obtained from the fitting of phase averaged spectra of EXO 2030+375 with BW model at different luminosities. The top, second and third panels of figure show the mass accretion rate, diffuse rate and the ratio of bulk to thermal Comptonization in accretion column, respectively. While the fourth, fifth and sixth panels indicate the luminosity variation of magnetic field, plasma temperature and column radius, respectively.
An interesting trend of parameter $\delta$ with luminosity was noticed in the third panel of the Figure 5.3. This parameter signifies the ratio of bulk to thermal Comptonization occurring in the accretion column. The value of $\delta$ was found close to unity at luminosity $\leq (3-4) \times 10^{37}$ ergs s$^{-1}$. This indicates that the effects of thermal and bulk Comptonization are nearly same in accretion column at lower luminosity of the pulsar. However, as the luminosity increases, the bulk Comptonization starts playing a major role in column emission. In comparison to the contribution of thermal Comptonization process in energizing the X-ray photons, it is seen that the bulk emission is higher by a factor of 20 as observed at lower luminosity.

The column radii ($r_0$), was found to strongly dependent on luminosity or mass accretion rate. An upper limit on the column radius $r_0$ is given by (Becker and Wolff, 2007, Eqn. 112).

$$r_0 \lesssim 6.5 \times 10^4 \left( \frac{B}{10^{12} G} \right)^{-2/7} \left( \frac{R_{NS}}{10 \text{ km}} \right)^{9/14} \left( \frac{M_{NS}}{M_\odot} \right)^{1/14} \left( \frac{M}{10^{17} \text{ g s}^{-1}} \right)^{1/7} \text{ cm}$$

Using the magnetic field value and mass accretion rate estimated for EXO 2030+375 at different luminosity, we have seen that the upper limit on column radius ranges in 400–650 m. Here the maximum value of upper limit correspond to the case of highest observed luminosity state of the pulsar as seen during peak of the Type II outburst (i.e Obs.-ID 91089-01-12-04, see Table 5.1). We note that the estimated values of $r_0$ in EXO 2030+375 are less than their upper estimates. At lower luminosities, in fact the $r_0$ values are an order of magnitude below the corresponding upper limits.

Moreover, the diffusion parameter $\xi$ was also observed to vary with source intensity, showing a minimum value at higher luminosity. An alternative view of $\xi$ is expressed by considering the ratio of dynamical time scale ($t_{\text{shock}}$) to the mean escape time scale ($t_{\text{esc}}$). Becker and Wolff (2007) define $t_{\text{shock}}$ to be the time scale during which the accretion material reaches the neutron star surface from the sonic point. And $t_{\text{esc}}$ is defined to be the time length for photons to diffuse through the walls of accretion column. The ratio of these two time scales is expressed as
\( t_{\text{shock}} \sim 0.24 \xi \) (see Equation 104 of Becker and Wolff 2007). In case of radiation dominated accretion flow in pulsars, Becker (1998) found the value of \( \xi \) to be \( \frac{2}{\sqrt{3}} \). In the present case of EXO 2030+375, we have seen that at higher accretion luminosity where the accretion is presumably radiation dominated, the value of \( \xi \) is close to 1. As per Becker (1998), in a radiation dominated pulsar accretion column, this condition ensures that the accretion flow halts at the stellar surface. This also represents the balance of escape time scale of photons from the accretion column with that of the accretion time scale. A more physical explanation of this behaviour is reflected from the requirement that the kinetic energy of the flow through the column walls should be radiated away within the time in which the gas settles onto the star. In case of EXO 2030+375, we have seen that at higher values of pulsar luminosity, this is indeed the case as the plasma is radiation dominated. However at lower luminosities, the value of \( \xi \) is higher than 1.

In addition to these, the electron plasma temperature was changing in the range of 3 to 7 keV. The temperature showed a gradual increase up to luminosity \( 4 \times 10^{37} \) ergs s\(^{-1}\). Beyond this, cooling of plasma temperature was observed. This may occur in the presence of strong radiation dominated accretion shock at which the in-falling matter mostly bulk Comptonize the seed photons that carries plasma energy by diffusing through the side walls of accretion column. It leads to the settling of plasma in accretion column at lower temperature. This model also provides an opportunity to constrain the magnetic field of the pulsar which is found to be in the range of \( \sim (4–6) \times 10^{12} \) G (see Figure 5.3). In some cases, magnetic field estimated from this model was found insensitive to upper value though their lower estimate was easily constrained in all these observations. Therefore, only best fitted values without error bars are quoted in Table 5.1.