Spectroscopic modelling of two high-mass X-ray binaries, Cyg X–3 and 4U 1538–522

Gargi Shaw1*, Sudip Bhattacharyya1
1Department of Astronomy and Astrophysics, Tata Institute of Fundamental Research, 1 Homi Bhabha Road, Colaba, Mumbai 400005, India

ABSTRACT
We report a detailed modelling of soft X-ray emission lines from two stellar-wind fed Galactic high mass X-ray binary (HMXB) systems, Cyg X-3 and 4U 1538-522, and estimate physical parameters, e.g., hydrogen density, radiation field, chemical abundances, wind velocity, etc. The spectral synthesis code CLOUDY is utilized for this modelling. We model highly ionised X-ray spectral lines such as Fe XXV (6.700 keV), Fe XXVI (6.966 keV), and reproduce the observed line flux values. We find that for Cyg X–3 and 4U 1538–522, the inner radius of the ionised gas is at a distance of $10^{12.25}$ cm and $10^{10.43}$ cm respectively from the primary star, which is the main source of ionisation. The densities of the ionised gas for Cyg X–3 and 4U 1538–522 are found to be $\sim 10^{11.35}$ cm$^{-3}$ and $10^{11.99}$ cm$^{-3}$, respectively. The corresponding wind velocities are 2000 km s$^{-1}$ and 1500 km s$^{-1}$. The respective predicted hydrogen column densities for Cyg X–3 and 4U 1538–522 are $10^{23.2}$ cm$^{-2}$ and $10^{22.25}$ cm$^{-2}$. In addition, we find that magnetic field affects the strength of the spectral lines through cyclotron cooling. Hence, we perform separate model comparisons including magnetic field for both the sources. Most of the parameters, except the hydrogen column density, have similar values with and without magnetic field. We estimate that the most probable strength of the magnetic field for Cyg X–3 and 4U 1538–522, where the Fe XXV and Fe XXVI lines originate, is $\sim 10^{2.5}$ G.

Key words: accretion, accretion discs – magnetic fields – stars: neutron – techniques: spectroscopic – X-rays: binaries: individual (4U 1538–52, Cyg X–3)

1 INTRODUCTION
X-ray binary (XRB) systems are co-rotating close binary stellar systems where the compact star is a neutron star or a black hole or a white dwarf, and the donor/companion star is a normal star or a white dwarf (Lewin et al. 1995; Sturm et al. 2012). XRB systems are classified in different groups depending on the nature of the compact star and the mass of the companion star (Reig 2011). High-mass X-ray binary (HMXB) systems are one among these classes where the compact star is a neutron star or a black hole, and the companion star is a massive star with a mass typically greater than ten solar mass (Liu et al. 2006). HMXB systems emit strong X-ray radiation (luminosity $\sim 10^{36} - 10^{40.5}$ erg s$^{-1}$) which are powered by mass accretion (Zeldovich & Guseynov 1966). Such accretion occurs via stellar wind (Bondi & Hoyle 1944) for most sources, but in some cases also through the Roche Lobe overflow (Frank, et al. 1992).

In the process of mass accretion via stellar wind, matter is blown away from the companion star and a small fraction of this matter gets captured by the compact object. The companion star of HMXBs are very massive and hence the matter gets thrown away at a high velocity close to a few thousand km s$^{-1}$. In such a system, the compact star is deeply embedded in the wind and the accreted matter heats up and shines in X-rays. Many HMXBs have so far been studied (Giacconi et al. 1967; Reynolds et al. 1992; Falanga et al. 2015, & references therein), and the X-ray spectral lines observed from them are sensitive to the underlying physical conditions of both the compact and the companion stars. Hence, if investigated properly, these X-ray lines can reveal a plethora of information about the binary systems.

In this work, we aim to do such a spectroscopic modelling of two HMXB systems using CLOUDY, and determine the underlying physical conditions like density, radiation field, chemical abundances, etc. For this purpose, we select two Galactic HMXB systems, Cyg X–3 and 4U 1538–522, which show multiple highly ionised X-ray spectral lines, including Fe XXV (6.700 keV) and Fe XXVI (6.966 keV).
keV). Fe XXVI and Fe XXV have H-like and He-like iso-electronic sequences, respectively. The He-like Fe XXV Kα complex includes three transitions involving 1s²1s2p, resulting into w(1S–1P), x(1S–3P2) and y(1S–3P1). The transition involving 1s²1s2s results into the forbidden line z (1S–3S) (Bianchi & Matt 2002; Bianchi et al. 2005). In a photoionised gas, H-like transitions are mainly produced by recombination, whereas the He-like transitions are produced by recombination and resonant scattering. In addition to this, the He-like transitions have a wide range of transition probabilities making them density sensitive (Osterbrock & Ferland 2006).

The neutron star in an HMXB has a strong surface magnetic field of $\sim 10^{12}$ G (Shapiro & Teukolsky 1984), which decreases as $\mu/r^3$, where $\mu$ is magnetic dipole moment and $r$ is the distance from the centre of the neutron star. On the other hand, the magnetic fields around black holes are expected to be small. For example, Dallilar et al. (2017) measured the magnetic field of the black hole V404 to be around a few hundred G. In many HMXBs, the companion star, and hence its wind, can also have a significant magnetic field. It is challenging to measure the magnetic field of the accreted material in an HMXB using Zeeman splitting or polarisation observations. Here, we suggest a plausible way to estimate the upper limit of the local magnetic field of the irradiated stellar wind of HMXBs, as mentioned below.

The presence of a magnetic field helps in cooling a high-temperature ionised gas through cyclotron emission. It takes dominant part in thermal cooling and contributes to gas pressure. This cooling is proportional to $B^2$. Hence magnetic field is capable to change the strength of emission/absorption lines from a high-temperature ionised gas. Therefore, the strengths of lines originating in such environments can be a suitable way to estimate an upper limit of the local magnetic field.

The HMXB Cyg X–3 was first observed by Giacconi et al. (1967) and 4U 1538–522 was first observed using Uhuru satellite by Giacconi et al. (1974). The nature of the compact object of Cyg X–3 is still ambiguous. It can be either a neutron star or a black hole. However, the compact object of 4U 1538–522 is a pulsar, and hence a neutron star. Observations (Vilhu et al. 2009; Reynolds et al. 1992) have indicated that the mass accretion rate for these two HMXB systems is via strong stellar winds of the companion stars. While HMXBs are well-studied, the effects of the magnetic field on the ionised spectral lines have not been explored. Here, we study such effects. Since a significant amount of data are available and more will be available in near future, our work can also be extended to many other similar HMXBs to derive their underlying physical conditions.

This paper is organised as follows. In section 2, we describe our models and calculations. Section 3 describes our findings and the results for the HMXB systems, Cyg X–3 and 4U 1538–522. In section 4, we summarise our results and conclusions.

2 CALCULATIONS

In this section we briefly present our numerical calculations which are carried out using the spectral synthesis code CLOUDY (https://nublado.org) which is a micro-physics code based on a self-consistent ab initio calculation of thermal, ionisation, and chemical balance of non-equilibrium gas and dust exposed to a source of radiation. It predicts the resultant spectra and vice versa over the entire range of the electromagnetic spectra using a minimum number of free parameters. We use an improved version of v17.02 of CLOUDY which includes 625 species including atoms, ions and molecules and utilises five distinct databases: H-like and He-like iso-electronic sequences (Porter et al. 2012), Stout (Lykins et al. 2015), CHIANTI (Landi et al. 2012), LAMBDa (Schoier et al. 2005), and the H₂ molecule (Shaw et al. 2005) to model spectral lines. The highly ionised lines modelled here belong to either H-like or He-like iso-electronic sequences. It is to be noted that atoms of the H-like iso-electronic sequence have one bound electron, and atoms of the He-like iso-electronic sequence have two bound electrons. CLOUDY uses a unified model for both the H-like and He-like iso-electronic sequences, that extends from H to Zn, as described by Porter et al. (2012). The new version, v17.02 of CLOUDY, uses improved energy levels of Ko transitions (Chakraborty et al. 2020a). The DR data used in Cloudy are taken mainly from http://anadpp.phys.strath.ac.uk/tamoc/DR/. A detailed description can be found in Ferland et al. (2013, 2017); Chakraborty et al. (2020b, c).

Previously, we have performed a spectroscopic modelling of highly-ionised X-ray lines from four low-mass X-ray binary (LMXB) systems (Shaw & Bhattacharyya 2019) using CLOUDY. In those LMXB systems, the mass transfer was via Roche Lobe overflow and the observed lines were originated in the associated accretion disc. In that work, we estimated various physical parameters like density, radiation field, chemical abundances and found that the highly ionised iron lines are sensitive to magnetic field. Based on this fact and the observed intensity of the highly ionised iron lines, we estimated an upper limit for the accretion disc magnetic field. Here our aim is to determine various physical parameters as well as to put an upper limit of the strength of the magnetic field where the highly ionized X-ray lines originate, following (Shaw & Bhattacharyya 2019). However, there is some differences in the current modelling. The HMXBs considered here are fed by stellar winds, whereas the previously studied LMXBs (Shaw & Bhattacharyya 2019) are fed through Roche Lobe overflow.

2.1 Models

The companion stars of Cyg X–3 and 4U 1538–522 are a Wolf-Rayet (WR; Kerckwijk et al. 1996) and a B0Iab star (Reynolds et al. 1992), respectively. The wind velocity profile from a super-giant (SG) star is described by $\beta$-velocity law (Castor et al. 1975),

$$v(r) = v_\infty \times (1 - r_{SG}/r)^{\beta}. \quad (1)$$

Here $\beta$ is velocity gradient and $v_\infty$ denotes the terminal velocity. In general, $v_\infty$ ranges from 1000 to 3000 km s$^{-1}$. For a steady-state wind, density profile $n_H(r)$ depends on the mass-loss rate $\dot{M}$. The hydrogen density profile $n_H(r)$ is given by the equation,

$$n_H(r) = \frac{\dot{M}}{4\pi r^2 n_H \mu v(r)}. \quad (2)$$
where $\mu$ and $m_H$ represent the mean molecular weight of the gas and mass of hydrogen atom, respectively. For simplicity, we assume $\beta = 0$ and a constant mass loss rate. As a result, the density decreases with distance in a power-law with a power $-2$,

$$n_H(r) \propto r^{-2}. \quad (3)$$

To be noted here that CLOUDY measures distance from the ionizing source which is fixed in the code. In our models, the compact star is the main source of X-ray ionization. Hence, we use the wind density distribution along the line of sight from the X-ray source calculated for a wind spherically symmetric with respect to the compact star. We consider the elemental abundances of the wind in our calculation. Earlier Szostek & Zdziarski (2008) also assumed similar density profile for Cyg-X3. Hence, we use the following radius dependent power-law density profile

$$n_H(r) = n_H(r_0) \times (r_0/r)^{-2}, \quad (4)$$

for all our models presented here. Here $n_H(r_0)$ is the density at the illuminated face at $r_0$ and the radius $r$ is centered on the compact star. For hydrogen density $n_H(r)$ (cm$^{-3}$), we use the total hydrogen density. In general, physical conditions vary at different phases of the orbit. In our model we incorporate this by using a covering factor, $f$, where $f$ is the fraction of 4$\pi$ sr covered by gas, as viewed from the central source of radiation. The value of $f$ lies between 0 to 1.

In our models presented here, we assume that the stellar wind is irradiated by radiation field coming from both the stars of the binary system. A blackbody is considered to explain the X-ray emission from and/or near the compact star. As a result, our considered radiation is composed of three components: i) a black body source appropriate to the companion star's temperature $T_{BB}$, ii) another blackbody continuum with temperature equivalent to a few tenths of one keV arising from the thermal emission near the compact star's surface (van der Meer et al. 2005), and iii) a Comptonised power-law continuum $\nu^{-\alpha}$. This power-law continuum behaves as $\nu^{\alpha/2}$ at lower energy to account for self-absorbed synchrotron (Rybicki & Lightman 1979), $\nu^{-2}$ at higher energies and $\nu^{\alpha}$ between 10 microns and 50 keV. The photon index, $\alpha$, is a free parameter. It is to be noted that, without considering the power-law continuum, we cannot predict the observed fluxes of Fe XXV and Fe XXVI lines.

To study the effect of magnetic field in our models, we use a tangled magnetic field (in units of G) following the equation

$$B = B_0 \times (n_H(r)/n_H(r_0))^{\gamma/2}. \quad (5)$$

where, $B_0$ is a free parameter and the term in parenthesis is the ratio of the density at a distance $r$ to the density at the illuminated face at $r_0$. The standard value of the adiabatic index $\gamma$ for a tangled magnetic field is 4/3. Lack of information on the angle between the radiation field of the central object and the magnetic field restrains us from using an ordered magnetic field. Here we propose that with a prior knowledge of other physical conditions, the strengths of highly ionised X-ray lines originating in the stellar wind of the companion star can be utilised to estimate an upper limit of the local magnetic field. Earlier, other modellers, e.g. Szostek & Zdziarski (2008), used CLOUDY to study the effect of X-ray on the stellar wind. The current updated c-17.02 version of CLOUDY uses improved energy levels of K$\alpha$ transitions (Chakraborty et al. 2020a) which improves the model predictions. In addition to that, we study the effects of magnetic field on highly ionised X-ray lines.

Cloudy has a built-in optimization process based on phymir algorithm (van Hoof 1997) which calculates a non-standard goodness-of-fit estimator $\chi^2$ and minimises it by varying input parameters. The $\chi^2$ is determined by the following relation,

$$\chi^2 = \sum_{i=1}^{n} \frac{(M_i - O_i)}{\min(M_i,O_i)} \sigma_i)^2. \quad (6)$$

Here, $n$ is the number of emission lines used in the model, $O_i$ is the observed value for the i-th observable, $M_i$ is the modelled value for this observable, and $\sigma_i$ is the relative error in the observed value. When the number of observed lines are greater than the number of input parameters, we use this method (Shaw et al. 2006, 2016). Otherwise, we perform a grid of models in the parameter space (within an acceptable range) (Mondal et al. 2019; Rawlins et al. 2018). We then pick the parameter values which predict better match to the observed values and finally fine-tune relevant input parameters so that the observed data can be matched maximally.

### 2.2 Effects of input parameters

Here we consider a sample model for HMXBs and show the effects of various input parameters on Fe XXV and Fe XXV line strengths as both the HMXBs considered here show Fe XXV and Fe XXVI lines. We assume a solar metallicity (Grevesse et al. 2010) stellar wind irradiated by radiation field coming from both the stars of the binary system consisting of (i) a blackbody source at 160,000 K with luminosity $10^{38.65}$ erg s$^{-1}$ mimicking the radiation from a WR companion star, (ii) another blackbody continuum with thermal emission from the compact star, and (iii) a Comptonised power-law continuum with a photon index 1.3 and luminosity $10^{39.3}$ erg s$^{-1}$. The temperature, at which Fe XXV and Fe XXVI lines form, is much higher than the sublimation temperatures of graphite and silicate dust grains. Hence we do not include dust in our calculation. Further, we assume $n_H(r_0) = 10^{12.5}$ cm$^{-3}$ and the wind velocity to be 1500 km s$^{-1}$. We do not resolve the binary stars to keep the uncertainties of the model low. The inner radius is $10^{11}$ cm away from the compact star and the extension of the ionized gas is set by a given column density of Hydrogen. For the sample model, this value is $10^{22.5}$ cm$^{-2}$. The sample model parameters are shown in Table 1. Fig.1 shows the total incident continuum and its constituting individual parts. Fig.2 shows the transmitted continuum of the sample model as a function of wavelength. The transmitted continuum consists of the attenuated incident continuum and the outward component of the diffuse continuum and line emission. The transmitting power of High Energy Transmission Grating (HETG) instrument on-board Chandra varies from 800 at 1.5 keV to 200 at 6 keV. We thus set the coarse continuum mesh resolution $E/\Delta E = 600$. The surface temperature of the companion star is much less than the excitation temperatures of Fe XXV and Fe.
Table 1. Input parameters for our sample HMXB model (see section 2.2.)

| Physical parameters                              | Values                        |
|-------------------------------------------------|-------------------------------|
| Power law: photon index, luminosity ( erg s$^{-1}$) | 1.3, 10$^{38.3}$             |
| $T_{BB}$ (companion star), luminosity ( erg s$^{-1}$) | 160000 K, $10^{38.65}$       |
| $T_{BB}$ (compact star), luminosity ( erg s$^{-1}$) | 0.7 keV, $10^{39.4}$         |
| Density $n(r_0)$ (cm$^{-3}$)                     | $10^{12.3}$                   |
| Inner radius $r_0$ (cm)                          | $10^{31}$                     |
| Wind (km s$^{-1}$)                               | 1500                          |
| Abundance                                        | Solar                         |
| Hydrogen column density $N(H)$ (cm$^{-2}$)       | $10^{22.5}$                   |

XXVI. Hence, the luminosities of Fe XXV and Fe XXVI lines do not depend on the surface temperature of the companion star. So, among all the parameters, the temperature of the blackbody continuum from the companion star surface has no effect on the fluxes of Fe XXV and Fe XXVI lines of the sample model. Therefore, we do not consider the blackbody radiation from the companion star while modelling Cyg X–3 and 4U 1538–522.

To gauge the effects of a parameter on the line fluxes, we only vary that parameter while keeping all others fixed. Table 2 shows how the line fluxes change with changing parameters.

Table 2. Effect of input parameters on Fe XXV and Fe XXVI line fluxes

| Parameter | Fe XXVI (erg s$^{-1}$) | Fe XXV (erg s$^{-1}$) | Fe XXV/Fe XXVI |
|-----------|------------------------|-----------------------|----------------|
| Default case | $10^{34.767}$ | $10^{33.937}$ | 0.148 |
| $n(r_0)=10^{12.6}$ (cm$^{-3}$) | $10^{34.806}$ | $10^{34.334}$ | 0.274 |
| $n(r_0)=10^{12.0}$ (cm$^{-3}$) | $10^{34.633}$ | $10^{33.569}$ | 0.086 |
| $T_{BB}$ | $10^{33.766}$ | $10^{31.724}$ | 0.09 |
| $N(H)=10^{23}$ cm$^{-2}$ | $10^{35.360}$ | $10^{34.901}$ | 0.347 |
| $N(H)=10^{22}$ cm$^{-2}$ | $10^{34.942}$ | $10^{33.378}$ | 0.122 |
| $Z=2 \times Z_{\odot}$ | $10^{34.991}$ | $10^{34.234}$ | 0.175 |
| $Z=0.5 \times Z_{\odot}$ | $10^{34.506}$ | $10^{33.638}$ | 0.135 |
| Photon index=1 | $10^{35.077}$ | $10^{35.018}$ | 0.873 |
| Photon index=1.6 | $10^{34.375}$ | $10^{33.008}$ | 0.04 |
| $T_{BB}=0.6$ keV | $10^{33.449}$ | $10^{33.662}$ | 0.169 |
| $T_{BB}=0.8$ keV | $10^{35.925}$ | $10^{33.988}$ | 0.092 |

We notice that the wind velocity has very negligible effect on the Fe XXV and Fe XXVI line fluxes. To check the effect of changing hydrogen number density, we change the density by ±0.3 dex from the default value, $10^{12.3}$ cm$^{-3}$. It is clear from the plot that the line fluxes are density dependent (below the critical density) and Fe XXV line is more sensitive as discussed in the introduction. Individual line fluxes as well as Fe XXV / Fe XXVI line ratio increase with increasing density. In the following, we discuss the effects of other parameters.

We vary the inner radius by ±0.3 dex from the default value to check its effect. For a given source luminosity, the radiation flux decreases as $r^{-2}$, and hence the temperature decreases with increasing inner radius. The collisional ionisation is temperature dependent, and its value decreases with decreasing temperature. Hence, individual line fluxes as well as Fe XXV / Fe XXVI line ratio increase with increasing inner radius. For the sample model, the effect of inner radius is more profound for Fe XXV.

The extension of the ionised gas is defined by $N(H)$. So, a higher $N(H)$ means a greater extension of the ionised cloud. As a result, the Fe XXV and Fe XXVI line fluxes increase with increasing $N(H)$. However, Fe XXV line flux increases more than the Fe XXVI line. Hence, Fe XXV/Fe XXVI ratio increases with increasing $N(H)$.

To check the effect of changing metallicity, the abundance of elements heavier than He, we change the metal-
licity by a factor of 2 from the default value. The density considered in the sample model are lower than the critical densities of Fe XXV and Fe XXVI. Hence, the luminosity of both the lines increases with increased metallicity. In addition to this, metallicity plays an important role in gas cooling. An increased metallicity decreases the gas temperature and affects physical processes which are temperature dependent. As discussed earlier, the collisional ionisation is temperature dependent. Hence, increased metallicity increases Fe XXV/Fe XXVI.

To check the effect of changing photon index of the power-law spectrum we run two models with photon index 1.0 and 1.6. The number of incident photon flux ($\propto \nu^{-\text{photon - index}}$) increases as photon index decreases, and it is more for smaller frequency. Hence, the line fluxes as well as Fe XXV/Fe XXVI increases as photon index decreases.

To check the effect of the compact star’s blackbody temperature, we run two cases with surface temperature 0.8 keV and 0.6 keV. A blackbody with a few tenth of keV temperature peaks in X-rays. Lowering this temperature reduces the height of the peak and shifts the peak to higher wavelengths. Hence, the continuum luminosity is affected by changing the blackbody temperature. The gas becomes less ionised and temperature also decreases with lower surface temperature. As a result, luminosity/intensity of the X-ray lines also decreases with decreasing surface temperature. With a higher surface temperature, the Fe XXV/Fe XXVI ratio decreases.

3 RESULTS

In this section, we present our results on HMXBs Cyg X–3 and 4U 1538–522, and elaborate on main findings. First, we discuss results of Cyg X–3 in detail. Then we discuss the results for 4U 1538–522.

3.1 Cyg X–3

Cyg X–3 ($20^\text{h} 32^\text{m} 25.78^\text{s}$, $+40^\circ 57' 27.9''$) (Cutri et al. 2003) is a well-observed HMXB in the constellation Cygnus, 7.4 kpc (McCollough et al. 2016) away from us. The nature of the compact star is not well understood, it can either be a neutron star or a black hole. Whereas, the companion star is not well understood, it can either be a kpc (McCollough et al. 2016) away from us. The nature of Cyg X–3 (20$^\text{h}$32$^\text{m}$25$^\text{s}$) is a well-observed HMXB in the constellation Cygnus, 7.4 kpc (McCollough et al. 2016) away from us. The nature of the compact star is not well understood, it can either be a neutron star or a black hole.

In this section, we present our results on HMXBs Cyg X–3 and 4U 1538–522, and elaborate on main findings. First, we discuss results of Cyg X–3 in detail. Then we discuss the results for 4U 1538–522.

To study the effect of magnetic field on highly ionised lines. In our model, we assume that the stellar wind is irradiated by the compact object with a blackbody temperatures 0.7 KeV. The corresponding luminosity is $10^{39-40}$ erg s$^{-1}$ (Vilhu et al. 2009). In addition to this, there is a Comptonised continuum having a power-law with the photon index $\alpha$. It is to be noted that the blackbody radiation from the companion star does not effect the X-ray line intensities. However, the metallicities of the companion star is important. We consider the typical Wolf-Rayet abundances assuming a WN(4-7) star: H=0.1, He=10, C=0.56, N=40, O=0.27 (Vilhu et al. 2009). The abundances of other elements are fixed at their solar values. In general, the stellar wind velocity of HMXBs range from 1000 to 3000 km s$^{-1}$ (Kaper 1995). In this model, we choose a stellar wind with velocity 2000 km s$^{-1}$. Vilhu et al. (2009) noticed that the line intensities are maximum around phase 0.5, when the compact star is in front. Here the geometry is complex, and as a first approximation we fix the value of the covering factor to be 0.25 for our simple model. From earlier literature we find that the value of photon index for this source is around 2 for soft X-ray observations (Koljonen et al. 2018). We choose 2 as the value of photon index for our model. We fix the elemental abundances with respect to hydrogen (in log scale) as, He/H = -0.071, N/H = -2.568, C/H = -3.822, O/H = -3.878, Fe/H = -4.500, S/H = -4.733, Si/H = -4.448, similar to a WN(4-7) star. Vilhu et al. (2009) performed an XSTAR simulation (Bautista & Kallman 2001) and predicted the hydrogen density at the illuminating face is close to this value. Our predicted hydrogen column density also matches to the value derived by Vilhu et al. (2009). The electron density (Fig. 4) and the electron temperature (Fig. 3) vary across the ionized gas. The value of electron temperature averaged over the extension of the
Table 3. Predicted model parameters of HMXB Cyg X–3 (without considering magnetic field) using CLOUDY (see section 3.1 for details).

| Physical parameters                  | Predicted values |
|--------------------------------------|------------------|
| Power law: luminosity (erg s\(^{-1}\)) | 10\(^{38.3}\)   |
| \(T_{BB}\) (compact star), luminosity (erg s\(^{-1}\)) | 0.7 keV, 10\(^{40.3}\) |
| Density \(n_H (r_0)\) (cm\(^{-3}\)) | 10\(^{11.35}\) |
| Wind (km s\(^{-1}\)) | 2000 |
| Hydrogen column density (cm\(^{-2}\)) | 10\(^{23.2}\) |
| Inner radius \(r_0\) (cm) | 10\(^{12.25}\) |

Figure 3. The variation of electron temperature as a function of distance from the compact star.

The variation of electron temperature as a function of distance from the compact star.

cloud is 9.05\(\times\)10\(^7\) K. Fig. 5 show the predicted transmitted spectra. In Table 3 we list the model parameters without considering any magnetic field.

In Table 4 we compare the observed and predicted luminosity of HMXB Cyg X–3. Our predicted luminosities for lines Fe XXVI, Si XIV, S XVI matches very well with the observation. Our predicted total luminosity for Fe XXV also matches with the observation, though the ratios among the Fe XXV lines do not match. It is to be noted that the ionising wind model of Vilhu et al. (2009) could not reproduce the observed line fluxes of Fe XXV and Fe XXVI. In addition to the observed lines mentioned in Vilhu et al. (2009), we also predict Ca XX and Ar XVIII with luminosity above 10\(^{34.5}\) erg s\(^{-1}\). These lines were not reported in Vilhu et al. (2009). This can be due to interstellar absorption and/or subsolar abundances of Ca and Ar. To check this, we run a model with Ca and Ar abundances lowered by a factor of -1 and -0.7 (in log scale), respectively. The predicted luminosities decrease by a factor of 10 and 5, respectively. Hence, we conclude that either the abundances of these two elements are subsolar (~ 1 dex lower) and/or there is absorption by interstellar medium.

Next, we include magnetic field in our model to study its effect on line intensities. Very hot ionised gas cools via cyclotron radiation, and we find that with a strength of the magnetic field \(\geq 10^3\) G, all the Fe XXV and Fe XXVI line fluxes exceed the observed ranges. At this point, the cyclotron cooling becomes the dominant cooling mechanism.

So, we reoptimise all the parameters including magnetic field. Table 5 and Table 6 list the predicted model parameters and the line luminosities, respectively. The variation of electron density and electron temperature have features similar to the previous case without magnetic field. However, the electron temperature averaged over the extension of the cloud is 8.66\(\times\)10\(^7\) K, less than the previous case without magnetic field. Our model predicts a magnetic field with strength \(10^{2.5}\) Gauss. The predicted spectra is similar to that of without magnetic field.

Previously Hubrig et al. (2016) had observed several
et al. (2014) have concluded the magnetic field to be \(327 \pm 141\) G. However, de la Chevrotière et al. (2010). Here also we do not consider dust grains, as expected. We consider typical solar abundances for this source (Grevesse et al. 2010). Here also we do not consider dust grains, as the temperature of the region where Fe XXV and Fe XXVI lines are observed by Aftab et al. (2019) for the eclipse position. We predict observed eclipse phase of HMXB 4U 1538–522. We predict observed X-ray lines. For calculation purpose, we multiply it with corresponding line centre energy and convert into ergs cm\(^{-2}\) s\(^{-1}\) unit. Here we consider \(f = 0.6\) for eclipse phase. Furthermore, we use 0.2 as the photon index as estimated by Aftab et al. (2019) for the eclipse phase.

Similar to the earlier system (Cyg X–3), we assume that the stellar wind is irradiated by the compact object with a blackbody temperatures of a few tenth of KeV and a power-law continuum. The blackbody radiation from the companion star has no effect on the X-ray lines, as expected. We consider typical solar abundances for this source (Grevesse et al. 2010). Here also we do not consider dust grains, as the temperature of the region where Fe XXV and Fe XXVI lines are observed by Aftab et al. (2019) for the eclipse position. For calculation purpose, we multiply it with corresponding line centre energy and convert into ergs cm\(^{-2}\) s\(^{-1}\) unit. Here we consider \(f = 0.6\) for eclipse phase. Furthermore, we use 0.2 as the photon index as estimated by Aftab et al. (2019) for the eclipse phase.

Table 8 compares the predicted and observed fluxes for eclipse phase of HMXB 4U 1538–522. We predict observed fluxes of both the Fe XXV and Fe XXVI lines simultaneously within the observed range. It is to be noted that the model parameters could be constrained better for this source if we have more observed lines of different species. The electron density (Fig. 7) and the electron temperature (Fig. 6) vary across the ionized gas. The value of electron temperature averaged over the extension of the cloud is \(10^{11.99}\) cm\(^{-3}\) and the illuminated face is \(10^{10.43}\) cm away from the compact star.

Table 7. Predicted model parameters of HMXB 4U 1538–522 using CLOUDY (without magnetic field).

| Physical parameters                  | Predicted values |
|--------------------------------------|------------------|
| Power law: Luminosity (erg s\(^{-1}\)) | 36.74            |
| \(T_{BB}\) (compact star), luminosity (erg s\(^{-1}\)) | 0.7 keV, 10\(^{38.1}\) |
| Density \(n_H(r_0)(\text{cm}^{-3})\) | 10\(^{11.36}\) |
| Wind (km s\(^{-1}\)) | 2000             |
| Hydrogen column density (cm\(^{-2}\)) | 10\(^{23.03}\)   |
| Inner radius \(r_0\) (cm) | 10\(^{12.3}\)    |
| Magnetic field (Gauss) | 10\(^{2.5}\)   |

Table 5. Predicted model parameters of HMXB Cyg X–3 (with magnetic field) using CLOUDY (see section 3.1 for details).

| Physical parameters                  | Predicted values |
|--------------------------------------|------------------|
| Power law: Luminosity (erg s\(^{-1}\)) | 10\(^{39.3}\)   |
| \(T_{BB}\) (compact star), luminosity (erg s\(^{-1}\)) | 0.7 keV, 10\(^{38.1}\) |
| Density \(n_H(r_0)(\text{cm}^{-3})\) | 10\(^{11.36}\) |
| Wind (km s\(^{-1}\)) | 2000             |
| Hydrogen column density (cm\(^{-2}\)) | 10\(^{23.03}\)   |
| Inner radius \(r_0\) (cm) | 10\(^{12.3}\)    |
| Magnetic field (Gauss) | 10\(^{2.5}\)   |

Table 6. Comparison of observed and predicted line luminosity (in units of 10\(^{35}\) erg s\(^{-1}\)) of HMXB Cyg X–3 using CLOUDY (without magnetic field).

| Observed Lines | \(\lambda\) (\AA) | Observed Lum | Predicted \(\lambda\) (\AA) | Predicted Lum |
|----------------|-------------------|--------------|-----------------------------|--------------|
| Si XIV         | 6.185             | 1.00±0.08    | Si XIV                      | 6.18223      |
| S XVI          | 4.733             | 1.80±0.10    | S XVI                       | 4.72915      |
| Fe XXV         | 1.859             | 3.38±0.60    | Fe XXV                      | 1.85951      |
| Fe XXV         | 1.869             | 2.62±0.60    | Fe XXV                      | 1.86819      |
| Fe XXV         | 1.852             | 1.42±0.60    | Fe XXV                      | 1.85040      |
| Fe XXV         | 1.780             | 6.05±0.50    | Fe XXV                      | 1.77982      |
| Ca XX          | 3.02028           | 1.69         | Ca XX                       | 3.02028      |
| Ar XVIII       | 3.73290           | 0.72         | Ar XVIII                    | 3.73290      |

Wolf-Rayet stars using FORS2 spectropolarimetry and estimated the highest value for the average longitudinal magnetic field to be \(327±141\) G. However, de la Chevrotière et al. (2014) have concluded \(0 < B_{\text{wind}} \leq 1700\) G based on spectropolarimetric study of a sample of 11 bright WR stars. Our predicted magnetic field (\(\approx 10^{2.5}\) G) is consistent with the observations of Hubrig et al. (2016).

Table 4. Comparison of observed and predicted line luminosity (in units of 10\(^{35}\) erg s\(^{-1}\)) of HMXB Cyg X–3 using CLOUDY (see section 3.1 for details).

| Observed Lines | \(\lambda\) (\AA) | Observed Lum | Predicted Lines | \(\lambda\) (\AA) | Predicted Lum |
|----------------|-------------------|--------------|----------------|-----------------|--------------|
| S XIV          | 6.185             | 1.00±0.08    | Si XIV         | 6.18223         |
| S XVI          | 4.733             | 1.80±0.10    | S XVI          | 4.72915         |
| Fe XXV         | 1.859             | 3.38±0.60    | Fe XXV         | 1.85951         |
| Fe XXV         | 1.869             | 2.62±0.60    | Fe XXV         | 1.86819         |
| Fe XXV         | 1.852             | 1.42±0.60    | Fe XXV         | 1.85040         |
| Fe XXV         | 1.780             | 6.05±0.50    | Fe XXV         | 1.77982         |
| Ca XX          | 3.02028           | 1.69         | Ca XX          | 3.02028         |
| Ar XVIII       | 3.73290           | 0.72         | Ar XVIII       | 3.73290         |

3.2 4U 1538–522

The HMXB 4U 1538–522 is an interesting eclipsing HMXB. It was first observed using UHURU satellite by Giacconi et al. (1974) and later followed by many observers. It is located at a distance of 6.4 kpc (Reynolds et al. 1992; Clark 2004; Bailer et al. 2018) with an orbital period of 3.73 days (Clark 2000; Baykal et al. 2006; Mukherjee et al. 2006; Falanga et al. 2015). This HMXB system is powered by the strong stellar...
Table 8. Comparison of observed and predicted line fluxes (in units of $10^{-13}$ erg cm$^{-2}$ s$^{-1}$) of HMXB 4U 1538–522 using CLOUDY (see section 3.2 for details).

| Lines          | Observed Flux | Predicted Flux |
|----------------|---------------|----------------|
| Fe XXV         | 2.04–1.62     | 1.85040        |
| Fe XXVI        | 1.55–1.35     | 1.77982        |

$^a$6.700 keV $^b$6.966 keV

Figure 6. The variation of electron temperature as a function of distance from the compact star.

Figure 7. The variation of electron density as a function of distance from the compact star.

we switch-on the magnetic field in our model to check its effects on the X-ray lines. We find that above a magnetic field $> 10^{3.5}$ G, the Fe XXVI and Fe XXVI line fluxes exceed the observed ranges. We believe this is caused due to cyclotron cooling. Next, like the earlier source, we reoptimise all the parameters including magnetic field. The predicted electron density, electron temperature, and the predicted spectra are similar to the case without magnetic field. Table 9 lists the predicted model parameters. The predicted magnetic field is $10^{2.5}$ Gauss. Table 10 compares the predicted and observed fluxes for eclipse phase of HMXB 4U 1538–522. Many groups estimated magnetic fields for OB stars (Przybilla et al. 2016; Castro, N et al. 2017) and found it to be of order of 1kG.
4 SUMMARY AND CONCLUSIONS

The HMXB systems are usual sources of strong X-ray lines. To understand these systems comprehensively, it is crucial to do a detail ab initio spectroscopic modeling of these X-ray lines. In this work, we carry out such a study using the spectral synthesis code CLOUDY, by self-consistently modelling the observed X-ray line intensities of Cyg X–3 (Vilhu et al. 2009) and 4U 1538–522 (Aftab et al. 2019). We assume these systems as highly-ionised gaseous stellar winds irradiated by a blackbody continuum with temperature equivalent to a few tenths of one keV of the thermal emission from the compact star, and a comptonised power-law continuum $\nu^{-\alpha}$ with photon index $\alpha$. The photon indices of the incident radiation of our models for Cyg X–3 and 4U 1538–522 are fixed to the observed values of 2 and 0.2, respectively. It is to be noted that the blackbody radiation arising from the companion star does not affect the highly ionised X-ray lines due to its low surface temperature. The presence of magnetic field cools high-temperature ionised gas through cyclotron emission and takes the dominant part in thermal cooling. Using the observed line intensities of the Fe XXV and Fe XXVI lines, we prescribe a plausible way to estimate the magnetic field cools high-temperature ionised gas through cyclotron emission and takes the dominant part in thermal cooling. Using the observed line intensities of the Fe XXV and Fe XXVI lines, we prescribe a plausible way to estimate the magnetic field.

4.4 SUMMARY AND CONCLUSIONS

The HMXB systems are usual sources of strong X-ray lines. To understand these systems comprehensively, it is crucial to do a detailed ab initio spectroscopic modeling of these X-ray lines. In this work, we carry out such a study using the spectral synthesis code CLOUDY, by self-consistently modeling the observed X-ray line intensities of Cyg X–3 (Vilhu et al. 2009) and 4U 1538–522 (Aftab et al. 2019). We assume these systems as highly-ionised gaseous stellar winds irradiated by a blackbody continuum with temperature equivalent to a few tenths of one keV of the thermal emission from the compact star, and a comptonised power-law continuum $\nu^{-\alpha}$ with photon index $\alpha$. The photon indices of the incident radiation of our models for Cyg X–3 and 4U 1538–522 are fixed to the observed values of 2 and 0.2, respectively. It is to be noted that the blackbody radiation arising from the companion star does not affect the highly ionised X-ray lines due to its low surface temperature. The presence of magnetic field cools high-temperature ionised gas through cyclotron emission and takes the dominant part in thermal cooling. Using the observed line intensities of the Fe XXV and Fe XXVI lines, we prescribe a plausible way to estimate the magnetic field.

5 ACKNOWLEDGEMENTS

Gargi Shaw acknowledges WOS-A grant (SR/WOS-A/PM-9/2017) from the Department of Science and Technology, India, and also like to thank the Department of Astronomy and Astrophysics, TIFR for its support. We thank the anonymous referee for his/her thoughtful suggestions.

6 DATA AVAILABILITY

Simulations in this paper made use of the code CLOUDY (c17.02), which can be down-loaded freely at https://www.nublado.org/. The model generated data are available on request.
Muller et al., 1987, Phys. Rev. A, 36, 599
Oskinova, L. M., Feldmeier, A., Kretschmar, P., 2012, MNRAS, 421, 2820
Donald E Osterbrock, Gary J Ferland, 2006, Astrophysics Of Gaseous Nebulae and Active Galactic Nuclei, 2nd edition, University science books
Paerels, F. et al., 2000, ApJ, 533, 135
Pahari et al., 2018, ApJL, 853, 11
Paradijs, J. van et al., 1984, A &AS, 55, 7
Przybilla, N. et al., 2016, A & A, 587, A7
Porter R. L., Ferland G. J., Storey P. J., & Detisch M. J., 2012, MNRAS, 425, L28
Rawlins, K., Srianand, R., Shaw, G., et al., 2018, MNRAS, 481, 2083
Reig, P., 2011, Ap&SS, 332, 1
Reynolds, A. P., Bell, S. A., & Hilditch, R. W., 1992, MNRAS, 256, 631
Reynolds A. P., Owens, A., Kaper, L., Parmar, A. N., Segreto, A., 1999, A & A, 349, 873
G. B. Rybicki and A. P. Lightman, Radiative processes in astrophysics. New York, Wiley-Interscience, 1979, 393p
Rodes-Roca, J. J., Page, K. L., Torrejon, J. M., Osborne, J. P., & Bernabeu, G., 2011, A & A, 526, A64
Schoier F. L., van der Tak F. F. S., van Dishoeck E. F., & Black J. H., 2005, AA, 432, 369
Shapiro, S. L., Teukolski, S. A., 1984, Black Holes, White Dwarfs and Neutron Stars, Wiley-Interscience, New York
Sturm, R., Haberl, F., Pietsch, W., et al., 2012, A&A, 537, A76
Szostek, A., & Zdziarski, Andrzej A., 2008, MNRAS, 375, 793
Shaw G., Ferland G. J., Abel N. P., et al., 2005, ApJ, 624, 794
Shaw G., Ferland G. J., Srianand, R., Abel, N. P., 2006, ApJ, 639, 941
Shaw G., Rawlins K., Srianand R., 2016, MNRAS, 459, 3234
Shaw G., Bhattacharyya S., 2019, MNRAS, 486, 195
Vilhu, o., Hakala, P., Hannikainen, D. C. et al., 2009, A&A, 501, 679
van Hoof, P. A. M., 1997, PhD thesis, Rijksuniversiteit Groningen 905
van der Meer, A. et al., 2005, A&A, 432, 999
van Kerckwijk M.H., Geballe T.R., King D.L. et al., 1996, A & A 314, 521
Zdziarski, A. A., Mikolajewska, J., Belczynski, K., 2013, MNRAS, 429, 104
Zeldovich, Y. B. & Guseynov, O. H. 1966, ApJ, 144 840

This paper has been typeset from a \TeX/LaTeX file prepared by the author.