Assessing the Impact of UV/X-Ray Emission from Accreting Black Holes on the ISM

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Abstract
Physical models of jets and accretion disks observed in X-ray binaries crucially depend on good multi-wavelength data from radio wavelengths to gamma rays. However, observations in the UV are very difficult to obtain, as most known black-hole binaries lie in the galactic plane and are thus heavily obscured by dust and gas which scatter, absorb and reprocess the emission. Yet it is at these wavelengths that observational constraints could make an important contribution to resolve the controversy between jet and corona models for the inner accretion region near the black hole in these sources. In this thesis, I explore the possibility of using the measured flux at long (optical and infrared) wavelengths to set constraints on the unknown UV luminosity by developing a physically realistic model for how radiation is reprocessed in the medium around two galactic X-ray binaries, Cygnus X-1 and GX 339-4. Employing the sophisticated photoionization code Cloudy and using Cygnus X-1 as a testbed, I explore a range of parameters and find that the characteristics of the resulting model spectrum crucially depend on the amount of material the radiation passes through before the simulation is stopped, but not strongly on the density structure of the nebula. I can therefore model rather complicated environment with a simple set of initial conditions. Strong constraints on the model come from tight radio/X-ray correlations, setting an upper limit to the total hydrogen column density in the model nebula. The resulting model spectra show strong nebular line emission in the far-infrared, as well as the presence of a continuum component produced by dust. The nebula is largely optically thin to UV radiation, making these nebular emission lines our best hope for constraining the UV emission. While this work is a first exploratory step towards our goal of discerning between jet models, the results show a clear capability of making physical predictions about the role of the ionized medium in the system. Observations with current and future infrared telescopes, together with further development of the model, will deliver the necessary observational and theoretical constraints to enable us to estimate the UV flux in X-ray binaries and consequently introduce a new method of distinguishing between jet and corona models. Implications for the importance of micro- and mini-quasars in early stages of the universe are discussed.
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1 Introduction

X-ray binaries (XRBs) consist of a compact object, a neutron star or a black hole, which accretes matter from a non-compact companion, for example a main-sequence star. They are among the most fascinating sources in the X-ray sky and their discovery is closely tied to the advent of X-ray astronomy itself: the first cosmic source found in X-rays during a rocket-flight experiment in 1962 was Scorpius X-1, the brightest X-ray source in the sky apart from our own sun (Giacconi et al., 1962). It was first believed that the X-ray emission originated in the Galactic Centre, but subsequent missions with more accurate astrometric data confirmed that it is indeed stellar (Bowyer et al., 1964). Since then, a variety of rocket, balloon and finally satellite missions have detected dozens of stellar X-ray sources in our galaxy. Their discovery quickly led to the question what kind of source could emit the observed X-rays, since main-sequence stars are not strong X-ray emitters. Shklovsky (1967) correctly identified accretion of matter onto a compact object as a possible mechanism for heating gas to X-ray emitting temperatures, and concluded that Scorpius X-1 was in fact a binary system where a neutron star accreted matter from a main-sequence or evolved companion star: an X-ray binary. Another surprise came in the form of Cygnus X-1, where optical spectroscopy of Doppler-shifted lines allowed mass estimates for the compact object, and found it to be too heavy to be a neutron star (Brucato & Kristian, 1973). This made Cygnus X-1 the first of several stellar-mass black hole candidates found in our galaxy as well as in the LMC.

Perhaps the most fascinating property of about XRBs is the fact that many sources frequently leave their quiescent state and show outbursts, where the source goes through a sequence of very different states (e.g. Belloni et al., 2005). Two states are of particular interest, lasting longer than the others. In one state, at the start of the outburst, X-ray emission above 10 keV (what X-ray astronomers call “hard” X-rays) completely dominates the spectrum, with only a minor contribution of photons at energies of a few keV (“soft” X-rays). Throughout this state, termed low-hard state (LHS), the X-ray luminosity increases by up to eight orders of magnitude. Subsequently, the X-ray spectrum changes shape drastically: the largest fraction of X-ray luminosity is found in the soft X-ray band and only a small power law-like component contributes to the spectrum at higher energies. The source has now entered the high-soft state (HSS). At the end of the outburst, the source then returns to the LHS before, except in a few persistent sources, fading back into quiescence.

Hundreds of observations of X-ray binaries at all accessible wavelengths have been performed over the decades, yet they continue to astonish and confound scientists. X-ray binaries are an incredibly diverse class of objects, both in terms of physical and observed properties. Many of the observed differences can be tied to physical variations in the system, making X-ray binaries a prime source for studying accretion physics and associated emission processes. Detailed monitoring campaigns at X-ray wavelengths revealed the existence of several intermediate states apart from the LHS and HSS mentioned above, and delivered a wealth of information about the physical processes that cause
the spectral changes. These processes are intimately tied to variations in the accretion process, for example if and where the accretion disc is truncated near the compact object. Radio observations have shown that some XRBs exhibit a collimated outflow in the form of a jet. In several sources, a compact, steady jet can be imaged in the radio during the LHS, and plasma ejections are visible during the transition from the LHS to the HSS. Additionally, the radio emission in the LHS is correlated with the X-ray emission, indicating an intimate relationship between jet and inner accretion flow. However, radio and X-ray flux are anti-correlated during the HSS, where the soft X-ray component, thought to originate in the accretion disc, dominates and the jet is believed to be quenched. Evidence for this jet behaviour comes from the observation that radio fluxes drop drastically, at least by a factor of $20 - 30$, during the HSS.

The presence of a jet in some black hole binary sources is interesting for several reasons. Most notably, these sources may present small-scale analogues of the jets ejected by supermassive black hole systems in active galactic nuclei (AGN), and especially the distant, radio-loud sources such as radio galaxies. For this reason, black hole binaries exhibiting jets are sometimes called microquasars after their massive cousins. It is often assumed that the relevant processes are the same, but quantities scale with mass. This includes the relevant time scales, and is the reason why black hole binaries are very valuable for studying the accretion physics in AGN; while the relevant time scales for supermassive black holes are of the order of millions of years, we can observe changes in X-ray binaries over just a few months, a much more viable time span to probe in an observational campaign. X-ray binaries may thus not only help us learn about accretion processes in general, but also aid us in understanding the processes that drive the central engines in quasars.

Despite the remarkable progress the field has made both in theoretical understanding and observational evidence, there are still fundamental questions that are unanswered. Our understanding of the accretion processes near the compact object is far from complete: in neutron-star binaries, strong magnetic fields complicate the accretion flow models considerably; in black hole binaries, the fact that the black hole does not have a solid boundary and consequently there cannot form a boundary layer between accretion disc and surface necessitates the presence of some sort of more complicated accretion flow. Additionally, it is not yet solved how and where jets are launched. Somewhere in the inner accretion disc, matter must be re-routed to the poles and ejected in a collimated outflow. How exactly this happens is a field of intense study in itself, but intimately tied to the nature of the accretion flow near the black hole. It is thought that magnetic fields play an important role in this process (Meier et al., 2001), and it is possible that the energy needed to launch a relativistic jet is extracted from the black hole itself, if the black hole is spinning (Koide et al., 2000). However, our understanding of black hole spin and its role in the jet-launching scenario is very limited. In the currently favoured model, the magnetic fields in the accretion disc around the black hole are dragged along by the spinning black hole. A tightening of magnetic field lines could then possibly launch the jet material (Blandford & Znajek, 1977).

The question which physical processes dominate in the inner region close to the black
hole is intimately tied to the question which processes produce the hard X-rays dominating the X-ray spectrum in the hard state, thought to originate in the inner accretion region. The prevalent model, the so-called Compton corona model, assumes that there is a hot, tenuous gas of highly energetic electrons upscattering accretion disc photons to hard X-ray energies. In the past years, this view has been called into question in favour of a more holistic approach incorporating the presence of magnetic fields and a jet-launching region. In this model, successfully applied to the galactic X-ray binaries XTE J1118+480 (Markoff et al., 2001) and GX 339-4 (Markoff et al., 2003, 2005) the role of the corona is assumed by the base of the jet, i.e. the region where the jet is launched and accelerated. Interestingly, in this latter model, which reproduces the observed hard X-ray spectrum very well, the base of the jet is also responsible for radiating a synchrotron spectrum producing a characteristic peak at UV wavelengths which is one of the discerning features of the jet model (Markoff et al., 2005). Unfortunately, progress in this area is somewhat hampered by observational constraints: many XRB sources are in the galactic plane, thus extinction in optical and most especially UV wavelengths is very large. Yet in order to constrain coronal and jet models, detailed knowledge of the flux at different wavelengths, as well the relative contributions of different spectral components to the total flux, is necessary.

The last point is where this thesis aims to make its contribution. The same processes that renders some optical and especially UV observations difficult in many cases may also turn out to be a blessing for the study of X-ray binaries. Absorption, photoionization, scattering and various other radiative transfer processes attenuate and modify the source spectrum. This influence must be taken into account when deriving conclusions from a spectrum, and relies on accurate modelling of the astrophysical processes present in the interstellar medium (ISM). On the other hand, if we can accurately estimate how much emission was reprocessed and in what way, we may be able to use that information to calculate back to the ionizing flux of the XRB. In the type of radiative transfer commonly encountered in photoionized nebulae around bright stellar sources - also called HII regions for their content of ionized hydrogen - UV and X-ray photons are absorbed by the medium, and re-emitted as optical or infrared photons at wavelengths where the nebula is optically thin and observable with telescopes. Thus combining detailed observations at optical and infrared wavelengths with a realistic model of the interactions of the source spectrum with the surrounding gas and dust may present us exactly with the kind of tool we need to add the missing piece to the XRB spectrum and distinguish between jet and Compton coronal models.

Evidence for this kind of interaction between microquasar and environment is hard to come by in galactic sources: emission from ISM gas is too diffuse to be detected as a large-scale nebula. It is not surprising then that our best example for a black hole binary surrounded by a photoionized nebula comes from an extragalactic source: LMC X-1 (Pakull & Angebault, 1986). The ionizing source in this system is so strong that it does not only completely ionize hydrogen in its surroundings, forming an HII region, but also ionizes elements that are much more resistant to losing their electrons: The
optical spectrum shows species such as HeII and HeIII, attesting to the unusually strong X-ray source in the centre. The ionization nebulae we do observe in galactic sources is postulated to be mostly shock-ionized, where the high-energy particles of the jet impact on the ISM and blow a cavity, instead of photoionized by the strong XRB radiation. One example found in our galaxy is Cygnus X-1 with its jet-inflated nebula (Gallo et al., 2005; Russell et al., 2007). Recently, a similar example has been detected in the galaxy NGC 7793 (Pakull et al., 2010). Both exhibit an excess of [OIII] line emission that is inconsistent with photoionization, but characteristic of gas ionized when an energetic shock passed through it.

In this work, I strive to add this missing puzzle piece by simulating the environment around a microquasar using an advanced photoionization code, Cloudy. I will develop a reasonably accurate model for the medium an XRB is embedded in, exemplified using the most-studied XRB source Cygnus X-1. I will show that the environment has a crucial impact on the source spectrum, that models are extremely sensitive to the choice of parameters, and consequently, that the latter is important for drawing conclusions about accretion physics in black hole sources. It should be noted that while this thesis has a clear focus on black hole binaries, X-ray binaries containing neutron stars are in fact not that dissimilar in many ways, and the methods and results developed and found here may well be adaptable to neutron-star binaries.

This thesis has the following layout: In Section 2 I will give a basic introduction into black hole binaries, their observations and the basics of their accretion physics; in Section 3 I will make the jump to HII regions and their formation, and in Section 4 I will unify both concepts and describe the observational evidence for photoionized nebulae around black hole binaries. Section 5 is devoted to the mechanics of the photoionization simulation code Cloudy. I then turn to the heart of the thesis, and explain how Cloudy can be used to model the environment around the galactic microquasar Cygnus X-1 (Section 6). Finally, Sections 6.5, 7.2, 8 and 9 present the results of the simulations and discuss them in the larger framework described above.

2 Black Hole Binaries

2.1 General Overview

Black hole binaries are gravitationally bound systems with two components, where one is a collapsed stellar object, a black hole, and the second component is a star during its main sequence or post-main sequence phase of evolution. The secondary star donates some of its mass to the compact object via Roche-lobe overflow or stellar winds. During the accretion process, very-high energy particles as well as copious amounts of radiation are produced, which can be observed on Earth.

The existence of this kind of object was postulated in the early 20th century in the context of Einstein’s theory of general relativity, and was confirmed with the detection of the first X-ray binaries in the 1960s with masses of the compact objects that were too
large to be neutron stars: up to a few tens of the mass of the sun. Black hole binaries exhibit many properties that are similar to quasi-stellar radio sources, or quasars, representing the active nuclei of distant galaxies harbouring a supermassive black hole. Due to the similarities that go beyond simple morphological analogies, black hole binaries are therefore often called microquasars (Mirabel & Rodríguez, 1998). Since the time and length scales of many physical processes depend on black hole mass, microquasars are ideal subjects to test theories on quasars, since they exhibit in principle the same processes, but on much shorter time scales. Additionally, since most observed XRBs are exclusively located in the galaxy, the smaller distances facilitate spatial and spectral studies. Shortly after the observation of the first XRB, it was discovered that presumed black hole binary systems often exhibited jet-like emission features (Fabian & Rees, 1979). The most prominent example of this class is SS433 (Figure 1).

![VLA radio image of the galactic microquasar SS433 and its corkscrew-shaped jets.](image)

From Blundell & Bowler (2004)

In another binary system, GRS 1915+105, it was first found that the jet plasma moves superluminally, a result that has subsequently been confirmed in several other binaries as well. This had been observed in extragalactic jets before, and was seen as a smoking gun for the analogy between quasars and microquasars (Mirabel & Rodríguez, 1994).

As for AGN, it was proposed that the accretion disc and jets are coupled. Indeed, it is reasonable to assume that the jet is fed by material from the accretion disc. However, how exactly this proceeds, and how the jet is launched, is still under debate. In general, one assumes that rotational energy of the black hole is evacuated through magneto-hydrodynamic processes into jets launched at the poles. The idea of disc-jet coupling has been strengthened by the discovery of a correlation between X-ray and infrared observations: a sudden fall in X-ray luminosity is observed, followed by ejection of jets initially visible in the infrared, later also in the radio waveband (Eikenberry et al., 1998; Fender et al., 1997). A similar sequence of dips in X-ray emission followed by ejection of bright, superluminally moving knots has been observed over a period of several years.
in the AGN of the distant galaxy 3C 120 (Marscher & Jorstad, 2006).

In the following, I will give a short introduction into the different properties of microquasars, starting with microquasar physics. I will then switch to the more observational side, describing the spectrum and the different canonical states. Finally, I will give two examples, one with a high-mass and one with a low-mass companion.

2.2 X-ray Binary Physics

At the heart of XRB physics is accretion of material from the companion onto the compact object. This can happen either when the star fills its Roche lobe (see Section 2.2.1 for details), or when the star is massive enough to emit a strong stellar wind that is captured by the compact object’s gravitational potential (Section 2.2.3). In either case, the material streaming towards the compact object will have some angular momentum, and therefore cannot fall onto the object directly. Instead, it will form an accretion disc around the object, with material initially settling on circular orbits around the source. Internal shear forces dissipate angular momentum though the material outward, causing it to spread into a disc where part of the material slowly spirals towards the centre of gravitational attraction and loses energy in the form of heat and radiation at the same time. Somewhere in the inner part of the accretion disc, material is somehow re-routed and accelerated into jets. The exact physical processes present in the accreting systems of X-ray binaries and AGN are under debate and an important topic of astrophysical research. Here, I focus on a simple introduction into Roche Lobe overflow and wind accretion, closely following (Frank et al., 2002) and give a hint on where current models go beyond the simple assumptions used to make the complicated physics in this kind of system tractable.

2.2.1 Roche Lobe Overflow

Roche lobe overflow, where the envelope of a star overflows into the gravitational potential of its companion object, is essentially a fluid dynamics problem in a rotating frame. Assuming the usual fluid approximations hold - there are enough interactions to allow for propagation of information through the medium, and the mean free path in the medium is much smaller than typical length scales - one can write down the Euler equation including Coriolis and centrifugal forces as:

\[
\frac{\partial \vec{v}}{\partial t} + (\vec{v} \cdot \nabla) \vec{v} = -\nabla \Phi_R - 2\vec{\omega} \times \vec{v} - \frac{1}{\rho} \nabla P .
\] (1)

The left-hand side is the so-called Lagrangian derivate of the velocity \( \frac{D\vec{v}}{Dt} = \frac{\partial \vec{v}}{\partial t} + (\vec{v} \cdot \nabla) \vec{v} \), describing the rate of change in the velocity while following a stream line moving with fluid velocity \( \vec{v} \). The first term on the right-hand side is the Roche potential and describes the gravitational force as well as the effect of centrifugal forces. The second term on the right-hand side in Equation 1 describes the Coriolis force and the last term expresses...
additional pressure gradients. $\vec{\omega}$ is the angular velocity with respect to an inertial frame defined above and $\rho$ is the density of the medium.

![Figure 2: IDL visualization of the gravitational potential for two gravitationally bound bodies with unequal masses (Roche potential). This figure presents a 2D cut of the 3D potential through the binary axis connecting the two masses. The axes show an arbitrary distance scale. The dumb-bell shaped potential surface connecting the gravitational wells of the masses, labelled $-0.75$ is the Roche Lobe, the point where the potentials meet is the Lagrangian point $L_1$.](image)

Two parameters require special attention when discussing an accreting system: the mass ratio $q = M_{\text{primary}}/M_{\text{secondary}}$ governs the shape of the equipotentials, and the binary separation $a$ sets the overall scale of the system. From here on, we assume the primary is the compact object, in our case a black hole, and the secondary is its non-compact companion star. The shape of the potential as seen by a test particle in the gravitational field depends on where the test particle is located: for a particle that is far away from the system ($r >> a$), the two binaries can approximately be viewed as one object located at the system’s center of mass. In very close vicinity to either object, on the other hand, the test particle will be near enough to one of the two stars that its potential dominates (see Figure 2 for a visualization). The test particle will see roughly circular equipotential surfaces that are somewhat distorted in the direction of the companion. The drop-shaped distortion of the potential increases with distance from the star up to a critical surface where the equipotentials of the two stars meet (the potential labelled $-0.75$ in Figure 2): The Roche lobe. The point where the potentials of the two masses touch is the Lagrange point $L_1$. At this point, a
saddle point of the function $\Phi_R$, it is energetically favourable for material close to $L_1$ to fall into the gravitational potential of the companion, hence creating the circumstances enabling the flow of material from one star to the other. The Euler equation requires that the stellar surface of the companion must conform to one of the equipotential surfaces. Therefore, the more of the Roche lobe the star fills, the more distorted the stellar surface will become, following the distorted gravitational potential. The level of distortion is determined by the mass ratio $q$, as the perturbation of the potential depends on the gravitational field of the compact object. If the star fills its Roche lobe, then there will necessarily be material located at $L_1$, and any velocity perturbation to that material will push it into the compact object’s potential, establishing the mass flow.

2.2.2 Formation of an Accretion Disc

What happens to the material after it passed into the Roche lobe of the primary object? Matter passing $L_1$ has a high angular momentum, as it rotates around the compact object in its frame with the binary’s orbital frequency. Therefore, it cannot simply fall onto the compact object (Frank et al., 2002). Assuming the flow is highly supersonic, pressure forces can be neglected. Additionally, one assumes that the initial conditions near $L_1$ have no effect on the trajectory of the material, which is therefore a ballistic path equivalent to releasing a test particle with a given angular momentum at rest at $L_1$ into the compact object’s gravitational field. The particle then settles on an elliptic orbit with a slow precession due to the perturbation by the secondary’s gravitational field.

One can find the so-called circularization radius $R_{\text{circ}}$, the radius at which the material eventually settles, by defining a circular velocity at this radius:

$$v_{\text{circ}}(R_{\text{circ}}) = \left(\frac{GM_{\text{BH}}}{R_{\text{circ}}}\right)^{1/2}.$$  

Furthermore, one sets $R_{\text{circ}}v_{\text{circ}}(R_{\text{circ}}) = b_{\text{BH}}^2\omega$, with $b_{\text{BH}}$ the distance from $L_1$ to the centre of the compact object’s gravitational potential, and rewrites the circularization radius as:

$$\frac{R_{\text{circ}}}{a} = \frac{4\pi^2}{GM_{\text{BH}}P^2 a^3} b_{\text{BH}}^4 \left(\frac{b_{\text{BH}}}{a}\right)^4 = (1 + q) \left(\frac{b_{\text{BH}}}{a}\right)^4.$$  

This radius is necessarily smaller than the Roche lobe radius in all cases, as otherwise material would fall back into the companion’s gravitational potential. For a compact object, it is also always larger than the stellar radius (Frank et al., 2002). There is one important caveat in this description above: it was assumed that only one particle is released from rest into the gravitational potential of the primary. In reality, however, it is a flow of material rather than a single particle that crosses $L_1$, is drawn into the gravitational field, and settles on elliptical orbits around the primary. While on its way, it will encounter the material that has already settled, giving rise to viscous dissipation, shocks and other dissipative processes that convert some of the energy of bulk orbital motion.
into internal heat motion. Having lost energy, the infalling particles cannot remain at the circularization radius, but will sink deeper into the gravitational potential, causing the disc material to spread inwards. Additionally, viscous dissipation within the forming disc transports angular momentum outwards, further stretching out the disc, with part of the material slowly spiralling inwards on approximately circular orbits, and some material spiralling outwards. The orbits can be described as Keplerian with an orbital velocity

$$\Omega_K(R) = \left(\frac{GM_{BH}}{R^3}\right)^{1/2}. \quad (3)$$

It is implied in the equation that self-gravity of the disc is neglected, thus assuming the mass concentrated in the disc is much smaller than the mass of the primary. The outer disc radius can, for obvious reasons, not exceed the Roche Lobe radius. In general one finds $R_{\text{outer}} > R_{\text{circ}}$ and therefore defines the circularization radius as minimum disc radius.

Some of the energy lost in the dissipative processes taking place in the disc will be emitted as radiation. The disc’s luminosity can be estimated by looking at the energy loss the material goes through as it falls into the black hole. Assuming the material starts out at negligible binding energies, then the energy lost during the accretion process equals the amount of binding energy the matter has when it is at the surface of the primary, defined as:

$$L_{\text{disc}} = \frac{GM_{BH}}{2R_{\text{inner}}} \dot{M} = \frac{1}{2} L_{\text{acc}}, \quad (4)$$

where $R_{\text{inner}}$ denotes the inner edge of the accretion disc and $L_{\text{acc}}$ is the accretion luminosity, or the luminosity that the system would have if all of the infalling material’s energy was released into radiation at the black hole’s horizon (assuming the accretion disc extended right down to the horizon). Note that for a rotating black hole, the inner edge of the accretion disc can extend further inward to the black hole, and consequently the of energy released in the accretion disc can be higher (see e.g. Rees, 1984). It follows from Equation 4 that approximately one half of the accretion luminosity is released in the disc. The other half must be released very close to the star, although not necessarily in the form of radiation, either in a boundary layer (e.g. in neutron stars) or by some other form of accretion flow (in black holes). How exactly this happens is still a matter of debate and will be discussed in some detail in Section 2.2.4 below.

### 2.2.3 Wind Accretion

Low-mass X-ray binaries (LMXBs), where the companion is a relatively low-mass, late-type star, accretion almost always proceeds via Roche-lobe overflow. In systems involving an O- or B-star companion (high-mass X-ray binary), an additional mode of mass transfer is possible and often dominant: the stellar wind typical for early-type stars may
significantly contribute to accretion in systems with a high-mass companion.

The simplest model assumes a spherically symmetric wind that follows a simple velocity law of the type

$$v(r) = v_\infty \left(1 - \frac{R_*}{r}\right)^{1/2},$$

where $v_\infty$ is the terminal wind velocity and $R_*$ is the radius of the star. In general, wind velocities exceed the thermal velocity in the medium by a factor of a hundred or so, making the flow highly supersonic. As wind particles leave the companion star in the radial direction, they will encounter the gravitational potential of the binary’s compact object. If their kinetic energy is smaller than the gravitational potential, then they will be caught in the black hole’s potential well, ultimately being accreted. The radius around the black hole at which this happens can be described by

$$r_{acc} \sim \frac{2GM_{BH}}{v_{rel}^2},$$

with $M_{BH}$ the mass of the black hole and $v_{rel} \approx (v_{BH}^2 + v_{wind}^2)^{1/2}$ the relative velocity between the two binary components. Since the material is highly supersonic, a strong bow shock is created approximately at a distance around $r_{acc}$ from the black hole. If it is assumed that the wind velocity is much greater than the velocity of the black hole - not a bad assumption for most known sources - then one may set $v_{rel} \approx v_{wind}$ and the fraction of mass accreted $\dot{M}$ in terms of mass loss $\dot{M}_{wind}$ (with a negative sign) by the companion is found:

$$\frac{\dot{M}}{-\dot{M}_{wind}} = \frac{1}{4} \left( \frac{M_{BH}}{M_*} \right)^2 \left( \frac{R_*}{a} \right)^2,$$

where $M_*$ and $R_*$ are the mass and the radius of the companion, and $a$ is the binary separation. The question whether this material has sufficient angular momentum to form an accretion disc can be answered by looking at the circularization radius, as in the case of Roche lobe overflow. The specific angular momentum of the captured material can be estimated to be $l \sim (1/4)r_{acc}^2\omega$, where $\omega$ is the orbital angular velocity of the binary. This is a factor of $(\frac{r_{acc}}{a})^2$ smaller than for Roche lobe overflow, indicating that it is more difficult to form an accretion disc from wind material than from material that is funneled via overflow. In full, the circularization radius can be derived as

$$\frac{R_{circ}}{a} = \frac{M_{BH}^3(M_{BH} + M_*)}{16\lambda(a)M_*^4} \left( \frac{R_*}{a} \right)^4.$$

Here, $\lambda(a)$ is a wind law describing how the wind parameters change with distance from the companion. In practice, it is very difficult to find the circularization radius: both theory and observations are far from making accurate predictions on what the wind law should be, and determining $r_{acc}$ is no easier. Additionally, it should be noted that this is the simplest case possible. It is believed that in practice, the wind is not actually
spherically symmetric, since the presence of a massive compact object in the vicinity may strongly alter the wind properties, which, in turn, also changes accretion and X-ray emission. Thus, considering a more complicated wind model is in order, by adding the effects of the gravitational force of the compact object as well as the centrifugal force due to orbital motion and rotation of the companion (Friend & Castor, 1982). The effective potential wind particles feel then becomes

$$\Phi(r, \theta) = -\frac{GM*}{r} - \frac{GM_BH}{(r^2 + a^2 - 2ar \cos \theta)^{1/2}} + \frac{GM_BH}{a^2} r \cos \theta - \frac{1}{2} \omega^2 r^2.$$ (8)

The first two terms describe the gravitational potential, the third term the centrifugal force due to orbital motion, and the last term the centrifugal force due to rotation of the companion. It is assumed that in the orbital plane the flow is directed radially outwards from the companion, i.e. the Coriolis force and any non-radial gradient in $\Phi$ are ignored. Additionally, the influence of X-rays on temperature and ionization structure of the wind is discounted. This introduces some error since X-ray binaries emit strong X-ray radiation originating in the accretion disc which irradiates the near side of the companion as well as stellar wind material. Finally, the formation of shocks, accretion wakes or discs around the compact object is ignored as well. This assumption holds as long as one assumes a position close enough to the black hole for the gravitational potential to be important, yet reasonably far away from the accretion radius.

Friend & Castor (1982) performed this kind of analysis for several X-ray binaries, among them the black hole binary Cygnus X-1. They find that for a close binary with a massive black hole and an O-type companion, the wind is strongly focused: Figure 3 shows that the stellar surface of the companion is much closer to the critical surface for Roche lobe overflow around $\theta = 0$ (i.e. on the axis connecting compact object and companion).
companion) than elsewhere (the companion is to the right in this figure). At $\theta = 0$ the mass loss rate is highest, but it subsequently drops quickly to its minimum until it asymptotically approaches 0.25. This indicates that not only part of the wind is captured onto the black hole, but that the presence of a compact object alters the wind ejection and flow itself, having an impact on the accretion rate and process.

2.2.4 Accretion Flows and Discs

The description above provides all the ingredients required to describe the formation and evolution of an accretion flow. One can use fluid dynamics conservation equations of mass, energy and angular momentum to describe how the matter settles into an accretion disc, and what the structure of that disc will be. In general, solutions to axially symmetric flows with gravity, pressure and rotations are manifold and allow for a wide variety of phenomena, depending on the assumptions made and parameters chosen. There are three solutions that are considered standard solutions for accretion problems: spherical accretion, where there is an infall of matter from every direction around the central object, thin discs, where the scale height $H \sim v_k R$ (with $v_k$ the Keplerian velocity at radius $R$) of the disc is much smaller than the outer disc radius $R$, and finally thick discs, where the latter does not hold. I will restrict my discussion here to the basic standard case of a thin disc, and point towards other solutions that are relevant for accretion onto black holes (further discussion can be found in Frank et al. (2002)).

For a thin disc, there are several assumptions to be made. First, assume that matter lies very close to the mid-plane $z = 0$ in cylindrical coordinates, and assume that matter moves with Keplerian velocity $\Omega_K$ - as defined in Equation 3 - in circles around the accreting object with mass $M$ and $R_*$ (note that this is a general discussion, and the special case for black holes, which do not have a solid boundary, will be considered later). Keplerian rotation implies an angular velocity $v_\phi = R\Omega_K(R)$. Additionally, it is assumed that the disc material experiences a small negative radial drift $v_R$ such that matter is eventually accreted. The disc is then described in terms of the surface density $\Sigma(R)$ by the two equations of mass and angular momentum conservation,

\[
R \frac{d\Sigma}{dt} + \frac{\partial}{\partial R} (R \Sigma v_R) = 0, \tag{9}
\]

\[
R \frac{\partial}{\partial t} (\Sigma R^2 \Omega) + \frac{\partial}{\partial R} (R \Sigma v_R R^2 \Omega) = \frac{1}{2\pi} \frac{\partial G}{\partial R}, \tag{10}
\]

where $G(R, t) = 2\pi R \nu \Sigma R^2 \frac{d\Omega}{dR}$ is an expression for the torque and $\nu$ is the kinematic viscosity that still needs to be defined. Making one further assumption, namely that $\frac{d\Omega}{dt} = 0$, the two equations for Keplerian orbits can be simplified:

\[
\frac{\partial \Sigma}{\partial t} = \frac{3}{R} \frac{\partial}{\partial R} \left( R^{1/2} \frac{\partial}{\partial R} [\nu \Sigma R^{1/2}] \right). \tag{11}
\]
This equation describes the time evolution of the surface mass density in a Keplerian disc, and is a non-linear diffusion equation.

The conservation equations are easy to solve for a steady disc, where time evolution is not important, i.e. when $\partial/\partial t = 0$. Then one finds from mass conservation:

$$R \Sigma v_R = \text{const.}$$

and consequently for the mass accretion rate

$$\dot{M} = 2\pi R \Sigma (-v_R).$$  \hspace{1cm} (12)

From momentum conservation one can conclude

$$R \Sigma v_R R^2 \Omega = \frac{G}{2\pi} + C,$$  \hspace{1cm} (13)

where $C$ is a constant. Even in this case, the kinematic viscosity $\nu$ still needs to be defined. One way to do this is the so-called $\alpha$-prescription, where $\nu = \alpha c_s H$. Here, $\alpha$ is a parameter which includes our ignorance about what the actual viscosity is, $c_s$ is the sound speed and $H$ the scale height. For thin, fully ionized accretion discs, observational evidence suggests typical values of $\alpha$ lie in the range $\sim 0.1 - 0.4$ (King et al., 2007). Together with some further assumptions, e.g. dropping the radiation pressure from the equation of state, this leads to the standard steady thin disc solution as proposed by Shakura and Sunyaev (see Frank et al., 2002, p. 93 for the full set of equations, or the original paper by Shakura & Sunyaev, 1973).

In the case of black holes it must be considered that a black hole does not have a solid boundary, and it is therefore impossible to form a boundary layer as with a normal star. Instead, the boundary condition for a black hole must be qualitatively different, as a significant fraction of the dissipated energy can be advected through the horizon. This is possible in two cases. In the first, the accretion rate is so low that the medium is thin enough for two-particle interactions - the main vehicle for radiative cooling - to be unimportant. Energy can thus not be efficiently radiated away. In the second case, the density is so high that the medium is optically thick and radiation is trapped and dragged down into the black hole. In this case, accretion rates can be higher than the Eddington accretion rate, yet to the observer it appears that the luminosity is far below the Eddington luminosity. In both cases, radiative cooling is inefficient, while advection into the black hole dominates, and these flows are thus aptly named advection-dominated accretion flows (ADAFs). In practice, the equations describing the accretion flow are quite difficult to solve, and especially the energy equation can be quite cumbersome to treat. One method for optically thin ADAFs to deal with the equations is to assume the equations are solved by power law solutions. Then, under self-similarity, the advected energy is simply a constant fraction of the generated energy. Using this result, as well as the conservation equations and a prescription for the kinematic viscosity, usually
\[ \nu = \alpha c s H = \alpha c_s^2 / \Omega_K, \] the system of equations becomes tractable.

Another approach in this framework are the so-called slim discs. This solution is found after eliminating the z-component in the conservation equation using some form of vertical integration in order to simplify the system of equations. We can then integrate both the mass continuity and momentum equations with respect to \( z \) to get equations that are simpler to solve. The solution turns out to be an intermediate solution between thin and thick discs, hence the name slim discs.

2.3 States and State Transitions in Black Hole Binaries

After treating the physics connected to accretion processes in XRBs, we shall now return to what we actually observe when pointing telescopes at black hole binaries. The first black hole binary candidate system observed was Cygnus X-1 (Bowyer et al., 1965). Surprisingly, the system exhibited transient qualities, with at least two very distinct states in the X-ray emission: a “low” state, in which the system was relatively dim and exhibited a hard X-ray spectrum with most of its X-ray luminosity at photon energies above 10 keV, and a bright, so-called “high” state, where the spectrum softened considerably and the largest fraction of energy was released in X-rays below 10 keV (Tananbaum et al., 1972; McConnell et al., 2002). Since then, many more systems have been observed, many of which show a similar pattern in transitions between different states (see e.g. Remillard & McClintock, 2006, for a review of 20 black hole systems). The system GX 339-4 went into an outburst phase in 2002/2003 (Smith et al., 2002) and repeatedly showed outbursts since. Its behaviour has markedly influenced the canonical, standard model of how black hole binaries evolve during outburst (see Figure 4 for the hardness intensity diagram and the canonical shape).

In the following, I will give a short introduction into the main states and their observational properties (following Belloni, 2010), not devoting many words to variability and timing qualities, only mentioning these where they are the defining factor in distinguishing states. It is furthermore important to note that while the low hard state (LHS) and the high soft state (HSS) are relatively well-defined and often observed, there are lively debates on the existence and properties of other states. This is not least the case because there is considerable variation between sources as well as between different outbursts of one source.

2.3.1 Low Hard State

The LHS is observed only in the beginning of an outburst, when the source moves out of its quiescent state, and at the end, shortly before it moves back into quiescence. On the hardness-intensity diagram (Figure 4), it can be found on the right side of the diagram where the spectrum is very hard and only varies in intensity (e.g. Belloni et al., 2005). In the first phase of an outburst, the brightness of a source rises within a short time, whereas the spectrum remains hard, with a spectral index of about 1.6-1.7 (path on the far right in Figure 4). Some sources never leave this hard state and only vary in
Figure 4: Hardness-intensity diagram for the 2002/2003 outburst of GX 339-4. The hardness-intensity diagram plots the count rate versus the ratio of high-energy (hard) X-ray luminosity to low-energy (soft) X-ray luminosity and possesses the canonical q-shaped “turtle head”. The points on the diagram are individual measurements taken during the outburst. The source moves on a track through the outburst, starting in the lower right-hand corner, moving up vertically through the diagram until it reaches a maximum luminosity (LHS). It then moves to the left in the diagram, (intermediate states). This is equivalent to a softening of the spectrum, i.e. an increase in soft X-ray flux as compared to hard X-rays. Once it has reached the left-hand side of the diagram, it is in the HSS. At the end of the outburst, the luminosity decreases, and the source moves back into the LHS via several intermediate states, and from the LHS back into quiescence. Found in Belloni (2010), adapted from (Belloni et al., 2005).

intensity (e.g. XTE J1118+480: Frontera et al., 2003). At the very end of an outburst, the source returns to the LHS (Homan & Belloni, 2005). Once it is reached, no more transitions are observed. The LHS is often associated with the presence of fast, compact jets (Fender, 2001) and the associated persistent emission of radiation at radio frequencies (e.g. Stirling et al., 2001).
2.3.2 Intermediate States

The transition to the hard-intermediate state (HIMS) takes place when the source has reached \( \gtrsim 0.1 L_{\text{Edd}} \), i.e. 10% of the Eddington luminosity, the maximum luminosity for which gas pressure of the source can balance its radiation pressure (Gierliński & Newton, 2006). Once the source enters HIMS, the intensity remains high, but the source spectrum softens strongly on a short timescale of usually less than a dozen days (Belloni et al., 2005). During this period, the power-law spectrum increases to a power-law index of about 2.5 (Homan & Belloni, 2005). Additionally, the appearance of a thermal disc component becomes notable. The transition to the soft-intermediate state (SIMS) is determined entirely by timing properties: a drop in the overall noise level and the appearance of a quasi-periodic variability. In the spectrum, a softening of the spectrum is sometimes visible. The jet is quenched and often the emission of discrete ejecta is visible as optically thin radio plasmons (e.g. Gallo, 2010; Fender et al., 2004). This abrupt transition associated with a change in hardness is also called the “jet line” (Belloni et al., 2005; Fender et al., 2004).

The SIMS differs only little then in its spectral properties, but is characterized by a lower level of variability. Once this state is reached, a number of transitions is observed, all of which involve moving to or from the SIMS. In some cases, even a crossing of the jet line and a short return to the HIMS is possible. These transitions are usually very fast and often involve quasi-periodic oscillations (Homan & Belloni, 2005).

2.3.3 High-Soft State

During the high-soft state, the spectral power-law index remains high, indicating a very soft spectrum that is dominated by a soft, thermal accretion disc component (Homan & Belloni, 2005). There is only a minor flux contribution in the form of a hard component (see Section 2.4 for details on the spectrum). Often, the radio flux is over a magnitude lower in the HSS than in the LHS, and in some sources vanishes completely (Fender et al., 1999).

2.3.4 Transitions Back to the LHS

At the end of an outburst, the source becomes increasingly harder, but now at a much lower total luminosity. The HIMS phase is similar to that at the beginning of the outburst, but with much smoother timing properties. The range of hardness covered is similar, but not identical. Finally, the SIMS covers a much smaller range in hardness.

2.4 The Spectrum

The radiation emitted by black hole binaries spans the whole electromagnetic spectrum, from low-energy radio emission to ultra-high energy \( \gamma \)-rays. Since emission from different regions dominates in different wavelength regimes, and because the physical processes in these regions do not operate independently from each other, the whole system must
be modeled holistically. However, disentangling the different components is difficult, and often ambiguous. Several components add to the spectrum: the accretion disc, the jets, the companion, and the corona, a region of very hot, tenuous gas. Which of these dominates the hard X-rays is still a matter of significant debate.

The radio- and mm-spectrum is very flat, sometimes even inverted and generally has very high brightness temperatures (e.g. Fender et al., 2000). Together with the presence of polarized emission, these properties are generally seen as evidence for the emission mechanism to be of the non-thermal variety. Note that the high brightness temperatures translate to a minimum linear size of the emission region, which, in some cases, are larger than the binary separation, and thus cannot come from any component of the binary except the jets (Corbel et al., 2000). Together with the persistent flux levels in the radio waveband that indicates that there might be a continuously replenished stream of relativistic plasma that leaves the system: a jet. There is evidence for the presence of a jet in X-ray binaries by direct observations of compact radio jets in some sources (e.g. Cygnus X-1: Stirling et al., 2001). Radio emission from binaries is often only seen in the low, hard state and quenched in the soft state (e.g. Fender et al., 1999). This observation agrees well with the idea that the spectrum comes from a jet which is not present in the high, soft state. In intermediate states, often near the jet line, emission of optically thin radio plasmons that travel outwards, often at superluminal speeds, can be seen (Mirabel & Rodríguez, 1994).

The jet spectrum is believed to originate in a superposition of many synchrotron spectra (Blandford & Konigl, 1979). In the magnetic fields of the plasma stream, electrons spiral around field lines and emit synchrotron radiation. The spectrum for a given electron distribution has a characteristic peaked shape with a positive power law up to the so-called synchrotron self-absorption frequency. For frequencies smaller than this frequency, the medium is optically thick and hence self-absorbed. Above this frequency, the medium is optically thin, and the spectrum changes into a power law with negative spectral index.

As the jet travels outwards, assuming a steady flow, the plasma thins out in density, but plasma properties and magnetic fields are conserved. This leads to a shift in electron distribution in going from one part of the jet to the next and, consequently, a shift in spectrum and synchrotron absorption frequency. Many individual synchrotron spectra contribute to the final spectrum, which, to the observer, looks flat up to the highest synchrotron self-absorption frequency observed in the system, usually somewhere in the sub-mm or infrared regime. It has been observed that some level of synchrotron emission from the jet extends into the X-ray band for black hole binaries even in low-luminosity systems (Blandford & Konigl, 1979).

Where the most power in the spectrum of a black-hole binary is released depends strongly on its state. In the LHS, the largest amount of power is released in the radio and infrared, i.e. through the jet. The the HSS, however, the X-ray luminosity from the accretion disc and inner region close to the black hole starts to dominate the spectrum. It is here where most of the gravitational energy released by material accreted onto the
compact object is lost via radiation. Consequently, the X-ray part of the spectrum is of great interest when trying to understand the physics involved in the emission processes. This is especially true for hard X-rays which are believed to come from a region very close to the black hole.

Figure 5: Broadband X-ray spectrum of Cygnus X-1 in the soft (red) and hard (blue) states from data of the BeppoSAX and Compton GRO missions. From McConnell et al. (2002).

Hard and soft spectral components are assumed to originate both from different physical processes as well as different geometrical configurations in the accretion disc. The soft component is often assumed to originate in a geometrically thin, but optically thick accretion disc of Shakura-Sunyaev type (Shakura & Sunyaev, 1973). The spectrum itself is then formed by a multitude of black body spectra that are emitted at different radii from the central source in the accretion disc and depend strongly on the temperature law within the disc. The total spectrum is a superposition of the individual spectra (multicolour disc black body model). This kind of model has been widely used, as it is relatively simple and fast to integrate numerically. However, it is only strictly valid for one particular inner boundary condition, and for a more accurate description of the observed soft X-ray emission, more realistic boundary conditions must be found, as well as other processes that may distort the black body spectra need to be accounted for. Additionally, the hard power law-like component seen in the high, soft state cannot be described by this kind of model. As will be presented below, there is considerable debate as to what produces the hard X-rays.

In the hard state, the luminosity of the multicolour black body spectrum is sometimes, but not always, reduced, while the hard component changes both shape and intensity as compared to the soft state (McConnell et al., 2002) (See Figure 5 for an illustration).
the classical picture that has been prevalent for decades, the hard spectrum is believed to be created predominantly by thermal Comptonization of accretion disc photons on very hot thermal electrons located in some inner region close to the black hole, often called the corona (e.g. Sunyaev & Truemper, 1979; Poutanen & Coppi, 1998). There is no clear consensus as to where this corona is located, but it is generally believed it has to be in the vicinity of the compact object. The geometrical interpretation of the different spectral state in this view is as follows (Gilfanov, 2010; Zdziarski & Gierliński, 2004): in the soft state, the Shakura-Sunyaev accretion disc responsible for the multicolour blackbody spectrum extends almost down to the black hole. Hence there is only
very little or no possibility for a hot corona to form, and the majority of accretion flow energy is released in the optically thick, geometrically thin accretion disc. Some hard emission may be caused by a non-stationary, non-uniform (i.e. patchy) corona above the accretion disc (Haardt et al., 1994), where buoyant magnetic field lines may create a plasma structure not unlike the sun’s corona. In the hard state, however, the disc is truncated at larger distances \(10^2 - 10^3 r_g\), \(r_g = (2GM_{BH})/c^2\), (Liu et al., 1999)) and the inner part of the accretion disc is evaporated into a hot, tenuous plasma that is optically thin but geometrically thick (e.g. Dove et al., 1997, and references therein). Here, the accretion flow energy is converted via Comptonization on hot (both thermal and nonthermal) distributions of electrons into the hard spectrum seen in the low, hard state. This type of geometry and a sketch of the resulting spectrum is presented in Figure 6. Disc photons enter the corona around the black hole and get upscattered. A fraction of these photons, in turn, are scattered back towards the accretion disc, where they are reprocessed into fluorescent lines (e.g. Fabian et al., 1989) or reflected into a continuum (e.g. Lightman & White, 1988).

Over the past ten years or so, this classical picture has been called into question. For one, a near-linear correlation between radio and X-ray fluxes in the LHS spectrum of GX339-4 necessitated a re-evaluation of the classical idea that the accretion flow and jets emit at different wavelengths and can be viewed as separate phenomena (Hannikainen et al., 1998). It is perhaps not surprising that there is a relationship between inflow and outflow in an XRB, but the correlation between radio and X-ray fluxes was found to be exceptionally tight, \(L_r \propto L_0^{0.7}\) (Corbel et al., 2000) and to hold over many orders of magnitude in change of source luminosity (Corbel et al., 2003a). This correlation has since been observed for all black-hole binaries for which good multi-wavelength data is available (Gallo et al., 2003), indicating that there may be an underlying universal process, although the correlation is not always as tight as in GX 339-4 (Xue & Cui, 2007). There are other arguments against the classical corona model. For one, in the hard state the spectrum is hard enough, while the signatures of reflection of coronal photons on the accretion disc are weak enough to present a problem to Compton coronal model. Several extensions to the classical picture have been proposed, such as a patchy corona (Stern et al., 1995) above the cooler accretion flow or high disc ionization (e.g. Ross et al., 1999), but all these models overlook a major shortcoming of most coronal models in general: they rarely treat magnetic fields, and do not incorporate the jet itself. Magnetic fields are thought to be present in the inner accretion flow (see e.g. De Villiers et al., 2003, for a model), and significantly change the assumptions made for Comptonization of disc photons. Additionally, the jet seen in radio imaging observations must be launched somewhere in the inner region, possibly via rerouting energy and plasma from the accretion flow, the associated magnetic fields and the black hole spin (Blandford & Znajek, 1977). How exactly this happens is still a matter of debate. As of yet it is also unclear whether the jet and corona are simply fed by the same energy reservoir, or whether the corona feeds the jet itself. The latter idea has been proposed by (Markoff et al., 2003, 2005). In their picture, the base of the jet itself assumes the role of a magnetic corona. The hard X-rays measured are then created via Comptonization as well, but predominantly
via inverse Compton scattering of synchrotron photons inside the jet (Markoff et al., 2005). Because the jet is mildly beamed in the region where it is launched, the accretion disc photons have a smaller energy density as compared to rest-frame synchrotron photons produced in the jet itself, and consequently have a smaller impact on the resulting Compton spectrum except for at the base of the jet where the electrons have not yet been accelerated from their initially thermal distribution into a power-law. It is interesting to note that this type of model also produces a synchrotron spectrum created by these thermal electrons at the base of the jet. This spectrum, also providing the seed photons for the synchrotron self-Compton emission seen in hard X-rays, has a maximum in the UV part of the spectrum and produces a characteristic “hump” at these wavelengths that is not present for pure Compton coronal models. Thus constraints on the UV flux, difficult to obtain due to the high interstellar absorption at these wavelengths for the known X-ray binaries, could be a deciding factor when trying to distinguish between the two models. To a large extent, this is the motivation for this work: if we can constrain the UV flux by looking at reprocessed emission into longer wavelengths, this may give us a reliable tool to distinguish between jet and purely coronal models.

Finally, emission in the infrared, optical and UV also depends strongly on the type of system. In high-mass X-ray binaries (HMXBs), these parts of the spectrum are often dominated by the O- or B-type companion star’s blackbody spectrum. Additionally, the jet spectrum is believed to extend noticeably into the IR and optical, as correlations between fluxes of different wavebands show (Coriat et al., 2009). The lower end of the accretion disc multicolour blackbody may extend into the UV range as well, and the optical components may contain reprocessed X-ray emission from the disc.

2.5 Examples

In the following, I will present two examples of X-ray binaries with black hole components. These are also the sources that have been used for the subsequent analysis.

2.5.1 Cygnus X-1

Cygnus X-1 is a well-studied galactic source that was first detected in X-rays during a balloon experiment in 1965 (Bowyer et al., 1965) as one of the brightest X-ray sources in the sky, with a distance of $2.1 \pm 0.1\text{kpc}$ (Massey et al., 1995). After detection of an optical counterpart HDE 226868 (Walborn, 1973), it was swiftly identified as a HMXB with an O9.7 Iab companion (Walborn, 1973; Gies & Bolton, 1986a). The determination of the mass of the X-ray source proved more difficult, but with all mass estimates ranging from $M_{BH} = 8.7 \pm 0.8M_\odot$ (Shaposhnikov & Titarchuk, 2007) to $M_{BH} = 13.5 - 29M_\odot$ (Ziółkowski, 2005), it was clear early on that the X-ray source is too heavy for a neutron star or white dwarf, making Cygnus X-1 the first stellar-mass black hole candidate. Since its detection, it has been observed and monitored for the last 35 years at all wavelengths from radio emission to high-energy $\gamma$-rays, making it one of the best-studied galactic sources.
Cygnus X-1 is a highly variable source. Most notably, it spends the majority of the time in the hard state, while transitioning to the soft state every so often, where the radio emission decreases significantly (e.g. Braes & Miley, 1976). In the hard state, both the X-ray and radio emission display a 5.6 day orbital period as well as a 150-day period which might be due to precession of a disc/jet-system. The very compact, collimated, $\sim 30$AU-long jet is visible only at radio wavelengths (Stirling et al., 2001), with a larger, $\sim 140$AU jet component launched during a period of X-ray state transitions (Fender et al., 2006).

Cygnus X-1 is located in the star-forming region Cygnus OB-3 in the constellation Cygnus. This region is a highly complex environment with active formation of stars, and therefore very difficult to describe. At an inferred distance of 2.1 kpc, Cygnus X-1 has a distance of around 61pc from the centre of a nearby association of massive stars in Cygnus OB3 that may be related to Cyg X-1 (Mirabel & Rodrigues, 2003). The connection between the two is strengthened by the fact that the massive star association and Cyg X-1 have similar projected speeds; the motion of both is directed in the galactic plane. Mirabel & Rodrigues (2003) find that Cyg X-1 has a relatively low speed of $9 \pm 2$km s$^{-1}$ relative to Cygnus OB3. This speed is consistent with random velocities of stars in expanding associations. This sets tight constraints on the amount of mass ejected in the explosion: only an estimated $(1.0 \pm 0.3)M_\odot$ could have been ejected suddenly to accelerate the binary without disruption to the measured projected velocity.

A lower limit on the progenitor mass can be inferred from Cygnus X-1’s connection to the massive star association: assuming the stars of the association and Cygnus X-1’s progenitors formed at the same time, about $5 \times 10^6$ years ago, one can set the lower limit for the black hole’s progenitor mass at about $40M_\odot$. Since the black hole is only of the order of $10M_\odot$, the progenitor must have lost about 30 solar masses before collapse. Only a fraction of that mass could have been lost via accretion, since the binary companion has a mass off approximately $18M_\odot$. Mirabel & Rodrigues (2003) conclude that the progenitor was likely a Wolf-Rayet-star, which subsequently collapsed into a black hole. There is no obvious supernova remnant associated with Cygnus X-1, and none is seen in either radio continuum, X-rays or atomic hydrogen surveys at the inferred position where Cygnus X-1 formed. The lack of a remnant implies that the star might have collapsed in a dark explosion without expulsion of outer layers. Both observations are important for the environment that is being modelled here: the lack of a supernova remnant implies that many of the assumptions we expect for an object inside a supernova remnant - low-density medium of mixed stellar and ISM composition, dust grains destroyed by supernova shock front - not to hold in this case. On the other hand, massive stars are known to inflate wind bubbles with parsec-scale radii in the late stages of their stellar evolution. It may thus well be that the binary is still within its wind-blown bubble, again implying low densities and a depletion of dust. Additionally, Cygnus X-1’s companion is a relatively massive O-type star, which itself loses mass through stellar winds. Even if most of this mass is directed onto the black hole as wind-fed accretion, some will be lost to the environment.
The best description of the environment can be found in two papers describing infrared observations of the system (Persi et al., 1980; Mirabel et al., 1996a) as well as the optical and radio observations of the jet-inflated nebula (Gallo et al., 2005; Russell et al., 2007). Early infrared observations using the 234 cm-telescope at the Wyoming Infrared Observatory by Persi et al. (1980) confirm an infrared excess above the stellar continuum at wavelengths longer than 3.6 μm. Using a simple model for the description of the companion’s spectrum, they estimate an infrared excess at 10 μm of $S_\nu = 83 \pm 25$ mJy, i.e. at least an order of magnitude higher than the flux estimated for the companion. They propose that this excess is mainly due to free-free and bound-free emission in the nebular material around the system. ISOCAM photometry in the (5.0 − 8.5) μm- and (12 − 18) μm-bands by Mirabel et al. (1996a) confirm this infrared excess. Additionally, they find an extended envelope of infrared emission of a size of about 15 arcsec around the system (or about 0.2 pc at a distance of 2.5 kpc), which they attribute to emission from a photoionized nebula around the source as well. However, they also note an increase in the infrared excess between 3.9 μm and 4.9 μm, and conclude that the excess may in fact be due to warm dust in the circumstellar envelope, and not due to free-free emission. Whatever the mechanism, this presents the best evidence for a circumstellar envelope that has been irradiated and consequently reprocesses some of the emission.

A large, ring-like nebular structure of radio emission can be observed at a distance of $\sim 10^6$ AU (Gallo et al., 2005), drawing an edge between a nearby HII region and the direction of the radio jet powered by Cygnus X-1. Since Cygnus X-1 moves perpendicularly to the jet direction in the sky (Mirabel & Rodrigues, 2003), it can be excluded that this structure is the supernova remnant from the explosion that created Cygnus X-1’s compact object. Instead, Russell et al. (2007) determine from their Hα detection and study of the same ring-like nebula that it consists of shock-ionized gas, consistent with a bubble inflated from a large-scale jet, assumed to be travelling in the dark and only observable by its impact on the surrounding medium. Gallo et al. (2005) constrain the pre-shock ISM particle densities from the jet energetics to be $\sim 1 - 300 \text{ cm}^{-3}$, at most three orders of magnitude higher than the average ISM density in the galaxy. In general, the environment around Cygnus X-1 seems to be rather inhomogeneous (Russell et al., 2007) at to vary smoothly across the a four-degree area around the source (Hartmann & Burton, 1997). Russell et al. (2007) adopt a column density along the line of sight of $N_H = (6.55 \pm 0.94) \times 10^{21}$ cm$^{-2}$. The can effectively be seen as upper limit to the column density for modelling purposes. In practice, this includes both a fraction that was ionized by the source, and a - most likely larger - fraction of interstellar gas in the line of sight. Unfortunately, there are no reliable measurements of the intrinsic column density of the ionized nebula around Cygnus X-1, thus the fraction which can be attributed to the ionized nebula around the source itself is hard to estimate.
2.5.2 GX 339-4

GX 339-4 was chosen for this work as a low-mass counterpart to Cygnus X-1. It was discovered with the OSO-7 satellite, its behaviour being unlike that of any other source up to then (Markert et al., 1973). It exhibits a great range of variability, going into outburst about once a year. It is often called the canonical black hole binary, since it shows all the canonical states from the low, hard state to the high, soft state and the occasional ”off” state, where no X-ray emission is observed. It was classified as an LMXB after a non-detection of the companion during VLT observations in the off-state placed very low upper bounds on the luminosity of the companion (Shahbaz et al., 2001), the evidence indicating that the companion is a K- or early M-type star. Therefore, unlike Cygnus X-1, it is fed by Roche-lobe overflow of the companion and not by accretion via a focussed wind. The nature of the compact source was deduced via spectral and timing characteristics (Sunyaev & Revnivtsev, 2000). The fact that even in a state of very low overall luminosity, the accretion disc dominates the companion, is favourable for the kind of analysis performed here: in Cygnus X-1, the companion dominates the photoionizing ultraviolet radiation, which renders drawing conclusions about the black hole system, especially the jet, very difficult. Here, we can look directly at the black hole and accretion-ejection processes, and how they are affected by the surrounding emission.

Most X-ray spectra in the luminous state are similar to that of Cygnus X-1 and are well-fitted by Comptonisation, however, the long-term evolution of GX 399-4 differs radically from that of Cygnus X-1: while the latter is a persistent source with a relatively steady mass accretion rate, that of GX 339-4 ranges over many orders of magnitude and is unstable. Additionally, GX 339-4 goes through a wider range of accretion states, making it the prime target for studying accretion-ejection processes of accreting black hole systems. Radio observations have revealed the presence of a compact jet in the low, hard state, and radio and X-ray luminosities are correlated. This compact jet is quenched in the high soft state. Optical spectra are dominated by the accretion disc, and the most prominent line, H\textalpha, shows a double peak, indicating that it originates in a rotating accretion disc where the emission is red- and blue-shifted depending on the direction of motion of the material relative to the observer (Smith et al., 1999).

Little is known about the environment of GX 339-4, or its distance. Zdziarski et al. (2004) place it at about 8 kpc, quoting their bounds as $6.4 \, \text{kpc} \lesssim d \lesssim 9.4 \, \text{kpc}$ from comparing the radius of a late K-star filling its Roche-lobe to the apparent diameter. They favour a position in the galactic bulge, reasoning that the peculiar redshift in Na D and Ca K lines in high-resolution spectra are similar to what has been seen from members of OB-associations in the galactic bulge, as well as the high peculiar velocity. There is much material in the line of sight, with strong interstellar absorption lines from at least nine clouds in the line of sight complicating observations due to large levels of extinction (Hynes et al., 2004). Beyond that, no information is available in the literature about the nature of GX 339-4’s environment.
3 HII Regions

3.1 General Overview

HII regions, the common name for diffuse photoionization nebulae, are bright, extended regions of emission that are seen both in our galaxy as well as many nearby galaxies. They are created when ultraviolet radiation from a bright, high-mass star, usually an O- or B-star, photoionizes the surrounding interstellar medium. They show emission line spectra that contain many major hydrogen and helium emission lines as well as forbidden lines of ions of common elements, such as nitrogen, oxygen and sulphur. A large fraction of this section is a summary of the classic textbooks by Osterbrock & Ferland (2006) and Spitzer (1998), except where other explicit references are given. The reader is directed to those two excellent sources for more details on individual parts.

HII regions in other galaxies are predominantly found in the spiral arms and can, in fact, be used to trace the spiral arms (Georgelin & Georgelin, 1976, e.g.). In our galaxy, an association is more difficult due to the position of the solar system, however, since all known HII regions in our galaxy except for the one nearest to us lie in the galactic plane, it stands to reason that a similar association is likely true for our galaxy. Often, HII regions are a combination of the photoionization nebulae of several high-temperature stars, such as associations of several O- and B-type stars (e.g. Oey & Kennicutt, 1997), as well as open clusters (for example Dutra & Bica, 2001). In these systems, the few hottest stars are the main source of energy. Typical stellar temperatures lie between $3 \times 10^4 \text{ K} < T_* < 5 \times 10^4 \text{ K}$. The roughly blackbody-type spectrum of these stars is very strong in the ultraviolet band. Photons at these frequencies, with energies above the ionization potential of hydrogen at 13.6 keV, encounter neutral gas on their way through the ISM. If they collide with an atom, particularly hydrogen, they may transfer their energy to an electron, which may subsequently overcome the potential of the electromagnetic force, and become unbound. The excess energy of the photon above the ionization energy is transferred to the electron as kinetic energy. Collisions between free electrons as well as with ions distribute this kinetic energy to maintain a Maxwellian velocity distribution with typically $5000 \text{ K} < T_{\text{HII}} < 20000 \text{ K}$.

The excess energy during recombination with ions is emitted again as a photon, in the case of hydrogen usually in the Paschen or Balmer continua of HI. Subsequently, the electron cascades down onto successively lower energy levels until it reaches the ground state. Since each of these transitions lead to photon emission, this process gives rise to many of the emission lines observed, such as Hα and Hβ emission. Note that this leads to destruction of UV photons in HII regions: while photoionizations use up a large fraction of the available UV photons, recombinations are usually seen as a cascade down many excited levels, each emitting a photon of longer wavelength. Since the probability for an electron to be at the ground state is much higher than the probabilities of individual excited states, HII regions are usually opaque to ionizing radiation in UV, but not for infrared radiation. Therefore, HII regions attenuate the stellar spectrum by absorbing much of the higher-energy radiation, and emitting it as lower-energy emission lines and continua. Collisions between thermal electrons and ions excite low-lying energy levels.
of the ion. Although downward radiation transitions have a low probability, collisional de-excitation has an even lower probability at the low densities typical for HII regions (generally \(n_e < 10^4 \text{cm}^{-3}\)). Therefore, almost every excitation leads to photon emission, which gives rise to the forbidden-line spectrum that is often observed. A more detailed explanation of the emission processes and resulting spectra will follow in Section 3.2.

In a typical HII region, hydrogen is ionized, helium is mostly singly ionized and higher-mass elements may exist in different ionization stages, but are in most cases singly or doubly ionized. Note that the degree of ionization at each point in the nebula is fixed by an equilibrium of photoionization and recapture, and may vary throughout the nebula. Near to the star, where the surface density of ionizing photons is high, the fraction of ionized gas is equally high. Further away from the star, the surface density of ionizing photons, and thus the ionization properties of the nebula change. Additionally, the fraction of ionized material depends on the temperature of the ionizing source, again via the number of emitted UV photons: a hot star emits considerably more UV photons than one with a lower surface temperature. It is seldomly possible to observe all important stages of ionization in a particular nebula. Therefore, modelling of the physical system is an important part of making sense of observations. In many nebulae, patches and condensations of neutral hydrogen are scattered throughout the region. As a whole, an HII region can be understood as a high-pressure bubble expanding into a lower-pressure medium: the internal motions in the gas have velocities of about 10 km s\(^{-1}\), which is of the order of the isothermal sound speed. Since this gas is at a temperature about two orders of magnitude higher than that of the surrounding interstellar medium, it expands into this colder material, decreasing the density within the nebula and increasing the ionized volume. The outer edge of the nebula is surrounded by an ionization front running into the neutral gas, where temperature, pressure as well as ionization fraction are discontinuous. Initially, when the massive star forms and "switches on", the ionized volume grows in size at a rate fixed by the rate of emission of the ionizing photons by the central source. The expansion halts when the pressures inside and outside the ionized nebula have equalized.

One important and very useful concept that is often used in the context of HII regions is the so-called Strömgren sphere (Strömgren, 1939). This is an idealization of the physical HII region, defined as the volume within the ionization front. Within this volume, part of the emitted photons is used to counteract recombinations in the gas, while the remaining photons cause the HII region to expand. The ionization front is then defined as the spherical surface at whose radius all Lyman continuum photons have been used to counteract recombinations. At this point, there is an equilibrium between the number of hydrogen-ionizing photons emitted by the central source \(S_H\) and the number of all recombinations in the gas:

\[
S_H = \frac{4\pi}{3} r_s^3 \alpha n_e n_{H^+} .
\]  (14)

\(r_s\) is the so-called Strömgren radius, i.e. the radius of the HII region, and \(\alpha\) is the recombination coefficient, describing how efficiently hydrogen recombines. Assuming
hydrogen is almost fully ionized, then we can write $n_{H^+} \simeq n_e \simeq n$, so that the expression for the Strömgren radius becomes

$$r_s = \left( \frac{3S_H}{4\pi \alpha} \right)^{1/3} n^{-2/3}.$$  \hspace{1cm} (15)$$

Consequently, the higher the gas density in the cloud, the smaller the HII region will be. For a typical HII region, illuminated by an O-star emitting of the order of $S_H = 10^{49} \text{s}^{-1}$ photons, we can assume a gas temperature of 10000 K, and a recombination coefficient of $\alpha \simeq 3 \times 10^{-13} \text{cm}^3 \text{s}^{-1}$. Using these values, we find for the Strömgren radius

$$r_s \simeq 60n^{-2/3} \text{pc}.$$  

Therefore, HII regions around young, massive stars that recently formed in a dense ($n \approx 10^4 \text{cm}^{-3}$) molecular cloud that is still present are very small, of the order of $r_s \approx 0.1 \text{pc}$. On the other hand, as explained above, even when all Lyman continuum photons are used to counteract recombinations in the HII region, it will still expand due to the pressure difference across the ionization front. The expansion leads to a smaller density in the cloud, which in turn decreases the probability of recombinations occurring: more hydrogen gas in the HII region can be ionized. If we assume a typical ISM gas density of $n = 1 \text{cm}^{-3}$, and an O-star as ionizing source as given above, we find that the HII region has a size of $r_s = 60 \text{pc}$. The expansion life time is

$$t_{\text{HII}} \simeq \frac{r_s}{c_s} \simeq 6 \times 10^6 \text{years}.$$  

This is similar to the main-sequence lifetime of an O-star, thus an HII region around such a star can not be much larger than the Strömgren radius, because it does not have time to expand further into the ISM before the star’s main sequence phase comes to an end.

### 3.2 Emission and Absorption Processes

There is a multitude of emission and absorption processes that affect the spectral energy distribution emerging on the far side of the nebula. Undoubtedly, photoionization of hydrogen, which removes a large fraction of the stellar UV radiation from the spectrum, and recombination, which adds strong emission lines of hydrogen, helium and other elements to the spectrum, are the dominant processes. The ionization state of the nebula at any point is then determined by an equilibrium of ionization and recombination processes of electrons with ions. In the following, I will give a short introduction into both, as well as other important line and continuum emission and absorption processes. All these processes are explained in more detail in (Osterbrock & Ferland, 2006).

#### 3.2.1 Photoionization and Recombination

Photoionization occurs when a photon with an energy higher than the binding energy of the electron on the outer shell of an atom is absorbed by this atom, and the photon’s
energy is transferred to the electron. The latter subsequently “jumps” from its shell. Any excess energy of the photon above the binding energy is transferred to the electron as kinetic energy. The interaction leaves behind a free electron and an ion: in the easiest case, hydrogen, a proton and an electron.

Assuming a gas of pure hydrogen, photoionization can then be described by

$$\text{H} + h\nu \rightarrow \text{H}^+ + e.$$  \hspace{1cm} (16)

The resulting numbers of ionizations per second and cm$^{-3}$ can be calculated as

$$N_{\text{ion}} = F_H \sigma_\nu n_H,$$  \hspace{1cm} (17)

i.e. it is proportional to the flux $F_H$ of ionizing photons and the particle number density $n_H$ of neutral hydrogen. The factor $\sigma_\nu$ is the absorption cross section and can often be taken as

$$\sigma \simeq 6.3 \times 10^{-18} \text{cm}^2,$$

ignoring the time dependence of the gaunt factor appearing in the definition of the absorption cross section, and assuming a gas of pure hydrogen.

Conversely, thermal electrons may be recaptured onto the excited levels of ions in a free-bound transition of the type

$$\text{H}^+ + e \rightarrow \text{H} + h\nu,$$  \hspace{1cm} (18)

i.e. the inverse transition of Equation 16. The number of recombinations $N_{\text{rec}}$ between an ion and electron to an energy level $n$ per unit time and volume can be estimated as

$$N_{\text{rec}} = n_{\text{H}^+} \alpha_n n_e,$$  \hspace{1cm} (19)

where $n_{\text{H}^+}$ is the number density of hydrogen ions in the gas, $n_e$ is the number density of free electrons, and $\alpha_n$ is the recombination coefficient to level $n$. When recombination to all levels $\geq n$ is considered, this becomes

$$\alpha^{(n)} = \frac{2.06 \times 10^{-11}}{\sqrt{T}} Z^2 \phi_n(\beta) \text{cm}^3 \text{s}^{-1}.$$  \hspace{1cm} (20)

Here, $\beta = \frac{h\nu_1}{kT}$ and $\nu_1$ is the frequency of the ionization edge, for hydrogen $h\nu_1 = 13.6\text{eV}$ or $\nu_1 = 912$ Å. $\phi_n(\beta)$ is the recombination coefficient function, whose values can be found tabulated in many books (e.g. Spitzer, 1998).

In a photoionized nebula, one assumes that all ionizations are balanced by recombinations, leading to the so-called ionization equation

$$n(\text{H}^0) \int_{\nu_0}^{\infty} \frac{4\pi J_\nu}{h\nu} a_\nu(\text{H}^0) d\nu = n(\text{H}^0) \Gamma(\text{H}^0) = n_e n_p \alpha_n,$$  \hspace{1cm} (21)

where $n_p = n_{\text{H}^+}$ is the number of protons, equal to the number of H$^+$ ions for a pure-hydrogen nebula, and $\Gamma(\text{H}^0)$ is the total number of ionizations, defined as the integral of the mean intensity over all frequencies of ionizing photons above the threshold $\nu_0$:
\[ \Gamma(H^0) = \int_{\nu_0}^{\infty} \frac{4\pi J_\nu}{h\nu} a_\nu(H^0) d\nu . \]

In this equation, the left-hand side describes ionization, and the right-hand side describes the number of recombinations per unit time and unit volume. To a first-order approximation, the mean intensity can be expressed in terms of the flux at the stellar surface \( F_\nu(R_\star) \), or alternatively the star’s luminosity \( L_\nu \):

\[ 4\pi J_\nu = \frac{R_\star^2}{r^2} \pi F_\nu(R_\star) = \frac{L_\nu}{4\pi r^2} . \]

It is often reasonable to assume that the lifetimes of excited states of hydrogen are very short, and thus all photoionizations are immediately balanced by recombinations, and that recombinations to excited levels are quickly followed by transitions to the ground state. Each recombination and transition emits a photon. Many of these photons have frequencies for which the nebula is optically thin. These photons can escape and be observed as typical emission lines (for bound-bound transitions of electrons down from excited levels) or a continuum (for free-bound transitions, i.e. recombinations into an excited state). Recombinations into the ground state, however, produce photons that are energetic enough to ionize other atoms. For nebulae with low hydrogen number densities, one can again assume the medium is optically thin, and these photons escape. For an optically thick nebula, however, this is not necessarily possible. In these cases, the so-called on-the-spot (OTS) approximation is often valuable: it is assumed that all photons of ionizing energy created in the nebula are absorbed elsewhere in the nebula, close to where they were created. Thus, one may assume no photons of this wavelength escapes the nebula.

If the photoionization cross section for hydrogen, or hydrogen-like atoms, is calculated as a function of photon energy, one finds that it is varies drastically over a range of UV frequencies. It is very high for relatively low frequencies \( \nu \approx 10^{16} \text{ Hz} \), but drops off roughly as \( \nu^{-3} \). Thus, high-energy photons are able to penetrate further into neutral gas before they are absorbed.

The photoionization equation above, together with the equation for radiative transfer

\[ \frac{dI_\nu}{ds} = -n(H^0) \alpha_\nu I_\nu + j_\nu , \]

can be solved in order to calculate the ionization structure of a pure-hydrogen nebula. Above, \( I_\nu \) is the specific intensity at frequency \( \nu \), \( s \) is the distance into the nebula, \( n(H^0) \) is the number density of neutral hydrogen and \( j_\nu \) is the coefficient of diffuse emission, also called source function. Models solving both equations numerically show that the ionization is near-complete almost out to the Strömgren radius, where the ionization drops quickly to zero. Most nebulae, however, do not consist of pure hydrogen, and therefore other elements need to be taken into account. The most abundant among those is helium. With an ionizing potential of 24.6 eV, ionizing helium requires higher-energy photons. \( \text{He}^+ \) ionization operates at even higher energies, \( h\nu \geq 54.4 \text{ eV} \). Even
the hottest O-stars emit only very little radiation at these frequencies, but other sources with X-ray-emitting components are known to create regions of doubly ionized helium around them.

The structure of a nebula containing both hydrogen and helium depends strongly on the abundance of helium-ionizing photons, as these are energetic enough to ionize both hydrogen and helium. If the flux above 24.6 eV is rather low, it will ionize all hydrogen and the remainder ionizes some helium. Consequently, one will see a small He\(^+\) region around the source, inside a larger HII region. The larger the fraction of helium-ionizing photons compared to photons that only ionize hydrogen, the larger the HeII region will be compared to the HII region. For the hottest stars, the boundaries of both regions coincide. The structure of a He\(^{++}\) region is analogous, but now depends on the relative luminosities above 54.4 eV and 24.6 eV, respectively. It should be noted that recombinations to He\(^+\) produce photons that can ionize hydrogen and must be taken into account when solving the ionization equation: HeII Lyman \(\alpha\) as well as Balmer continuum photons are absorbed by hydrogen and maintain the ionization of hydrogen in the He\(^{++}\) region, where stellar radiation with 13.6 eV < \(\nu\) < 54.4 eV is absorbed only by He\(^+\).

### 3.2.2 Free-Free Emission

Free-free emission, or commonly called bremsstrahlung, does not involve recombination, but rather the acceleration of free electrons on ions, where the electron remains free. The changes in energy of the particle due to collisions are continuous, and thus the resulting spectrum of radiation will be continuous as well. It can extend over a large range of frequencies, from radio up to X-rays for some astrophysical plasmas. In general, proper treatment of the acceleration of charges in the Coulomb field of other charges can only be done within the framework of quantum electrodynamics. However, in the low-frequency limit a classical or semi-classical treatment is possible and sufficient (for a simple introduction, see Rosswog & Bruggen, 2003; for a more thorough treatment, see Rybicki & Lightman, 1986). Bremsstrahlung mostly arises from weak collisions, as strong collisions are relatively rare, and because of the large differences in mass between ions and electrons, it is mostly the electrons that are accelerated, while one may assume the ion remains at rest. Furthermore, it is often assumed that the electrons are thermal, i.e. have a Maxwellian velocity distribution. Using these assumptions, and solving the equation for dipole radiation, one can derive the spectrum for free-free radiation:

\[
\frac{dW}{dV dt d\nu} = \frac{2 e^6}{3 mc^3} \left(\frac{2\pi}{3km}\right)^{1/2} Z n_e n_{ion} T^{-1/2} \exp(-h\nu/kT) \tilde{g}_{ff}^{\nu},
\]

where \(m\) is the mass of the electron, \(T\) is the electron temperature of the plasma, and \(\tilde{g}_{ff}^{\nu}\) is the so-called velocity-averaged gaunt factor. The spectrum resulting from free-free emission is largely flat up to a critical cut-off frequency \(\nu_c \propto \frac{kT}{\pi}\). At very low energies, the emission is self-absorbed and falls off as \(\propto \nu^{-2}\).
### 3.2.3 Dust Emission

The most obvious effect of dust in the interstellar medium on radiation from stars or other sources is extinction of emission from these sources. In the optical waveband, this extinction is largely due to scattering of radiation out of the beam, but some emission is absorbed by the dust grains themselves. We can define an extinction law

\[
I_{\lambda} = I_{\lambda,0}e^{-\tau_{\lambda}},
\]

where \(I_{\lambda}\) is the observed flux, \(I_{\lambda,0}\) is the flux that would be observed without the presence of dust extinction, and \(\tau_{\lambda}\) is the optical depth at the observed wavelengths. This law, however, only applies if no radiation is scattered into the beam, which - as can be seen e.g. from UV observations of quasars - is a distinct possibility in some cases. Interstellar extinction due to dust grains largely depends on grain properties such as their size distribution and composition as well as the column density of material along the line of sight: the more material there is between us and the object, the more emission will be absorbed or scattered out of the beam.

However, dust is also present in HII regions themselves, where it interacts with the radiation field of the central source as well as the gaseous component of the nebula. The presence of dust can be inferred both from photometry - many HII region show dark spots where the optical depth is higher than elsewhere in the nebula - and from spectroscopy, where the spectral features in the far-infrared due to dust grains are apparent. The dust grains scatter the continuous radiation of stars immersed in the nebula, which creates an observable nebular continuum. Furthermore, the dust grains absorb photons whose energy is subsequently converted into heat. In the infrared part of the spectrum, dust can be identified by its thermal emission. This thermal emission can be orders of magnitude higher than the free-free emission for the same column density, and is thus readily visible in infrared spectra. Heating of dust grains is primarily done by UV and optical photons from the central source, and possibly from nearby nebular gas that was ionized by these sources. The dust grains are heated to a certain equilibrium temperature and emit - to a first-order approximation - a dilute blackbody spectrum with a peak at that blackbody temperature, usually of the order of 100 K. However, more accurate measurements show that the shape of the spectrum does not closely follow a Planck function for any particular dust temperature or even a range of temperatures. More precisely, the spectrum has a relatively sharp peak similar to that observed in cool stars. This feature is commonly attributed to the presence of silicate grains. Additionally, one may observe narrower features at wavelengths of a few microns, particularly \(\lambda\lambda3.28,3.4,6.2,7.7,8.6\) and \(11.3\mu m\). These features observed in some HII regions are generally too broad to be emission lines of ions, and are likely to be the result of infrared fluorescence lines from vibrationally excited polycyclic aromatic hydrocarbons (PAHs) with around 20 – 50 atoms. These large molecules, when excited by UV radiation, decay to excited vibrational levels which emit the observed bands as they decay to the ground state.
It is difficult to study dust in HII regions quantitatively. The study of absorption features due to overdensities in the nebula is almost entirely restricted to the determination of the optical depth. Nevertheless, interesting results can be gleaned from the few avenues of analysis that are open. For example, knowing the optical depths enables us to calculate the amount of dust, if the optical properties of the nebula are known. Additionally, if the dust-to-gas ratio is known, then the mass of the entire structure can be calculated.

3.2.4 High-Energy Processes

Unlike a stellar radiation continuum, which even for the hottest stars does not reach far beyond UV wavelengths, an XRB - as the name suggests - emits copious amounts of high-energy radiation in the keV-range and at even higher energies. At these frequencies, different processes need to be taken into account that are not present in nebulae around stellar sources. For example, high-energy photons can remove electrons from the inner-electron shells of heavy-element atoms and ions, particularly the so-called K-, L- and M-shell (in X-ray nomenclature). These correspond to the three innermost shells of heavy atoms. X-ray photons can knock electrons off these shells because their energies are much higher than the ionization threshold of the outer (valence) shell. When this happens, an electron can jump out of the atom or ion system, leaving a “hole” on the inner shell. This hole can be filled by outer-shell electrons which jump down, and conserve energy by emitting a lower-energy photon and by ejecting outer electrons. The former process is also termed fluorescence, while the latter is called the Auger effect. The fluorescent emission from downward-cascading electrons forms emission lines, which are named in analogy to the hydrogen recombination lines $\text{K}\alpha$ (for the transition from the L- to the K-shell), $\text{K}\beta$ (for a transition form the M- to the K-shell) etc.

The rest of the electron’s energy that is not emitted via photons is transferred to other electrons, which are then either excited to levels above the valence shell or ejected straight away. The former case is often followed by auto-ionization, i.e. the spontaneous ejection of an electron. In the latter case, the efficiency of electron ejection strongly depends on the ability of bound electrons to rearrange themselves without emitting a photon. Heavy elements like iron, for example, will eject several outer electrons and produce a rich spectrum of fluorescent emission lines. The removal of a K-shell electron typically results in ions as high as Fe$^{9+}$ and a fluorescence spectrum involving dozens of lines throughout the far-UV and X-ray spectrum.

Another important effect at high energies is the Compton effect, where photons are scattered by an electron.

If the energy of the electrons $kT$ is larger than the photon energy, then the photon can gain energy following the collision. This is known as the inverse Compton effect (IC). The other extreme occurs when the photon energy is higher than the binding energy of some atoms in a medium. In this case, the highly energetic photons can transfer enough energy to an outer electron during elastic collisions to ionize the atom. Photons with an energy $\geq 2.3\text{ keV}$ will ionize hydrogen via Compton recoil.
The processes mentioned above, together with the effect of other high-energy processes such as pair-production and interaction with cosmic rays, produce electrons with energies higher than the kinetic energy of thermal electrons in the medium. These electrons are thus termed “supra-thermal” electrons and frequently undergo collisions with thermal electrons, effectively heating the medium. In predominantly neutral gas they may also cause collisional ionization and line excitation of strong permitted lines such as Hα before interacting with free electrons.

3.2.5 The Spectrum

The spectrum that can be seen from an HII region is a combination of the transmitted emission from the central ionizing source and emission created in reprocessing the absorbed stellar UV radiation. The latter depends on the abundances of the elements, determined by the previous evolutionary history of the gas, as well as the local ionization state, temperature and density. Emission lines are the prominent feature and are indicative of recombination processes. The emission line spectra are dominated by forbidden lines of ions of common elements, e.g. [O III] \(\lambda\lambda 4959\text{Å}, 5007\text{Å}, [N II]\lambda 6548\text{Å}, 6583\text{Å} \text{ and} [S III] \lambda\lambda 9069\text{Å}, 9523\text{Å} \text{ and} \text{H}β \lambda 4861\text{Å}, \text{can be observed. Weak continuous spectra of atomic and reflection components are present, but the majority of continuous nebular emission comes from free-bound transitions in the Paschen continuum of HI at } \lambda > 3646\text{Å} \text{ and the Balmer continuum at } 912\text{Å} < \lambda < 3646\text{Å}. Many nebulae also show reflection continua of starlight scattered by dust. In the infrared, emission from dust heated by the stellar continuum to about 100 K creates a continuum excess. This process, however, is not efficient in the radio, where free-free emission or bremsstrahlung of thermal electrons accelerated on Coulomb collisions with protons dominates. At these wavelengths, bound-bound transitions at very high levels can be seen as superimposed weak hydrogen emission lines.

3.3 Physical Properties of Photoionized Regions Derived from Spectral Features

Observations of nebulae around hot stars and other bright sources can provide valuable information about both the properties of the surrounding medium and the source of radiation itself. For example, one can determine the temperature of the nebula, as well as electron densities, from measurements of emission-line fluxes of recombination lines. The temperature of the central source - if it is a main sequence star - can be determined via the calculation of the total ionizing radiation that the source emits. For the type of analysis proposed in this work, this number of reprocessed photons itself is a valuable result, since it practically represents the UV flux that is so elusive to measure in XRB sources. Therefore, I will explain the line of reasoning behind this method in some detail. The basic assumption that goes into this technique is that the nebula is optically thick in the Lyman continuum, i.e. the continuum that provides the ionizing photons. Under
this assumption, the nebula will absorb all UV photons in this wavelength range, so that
the total number of ionizations in the nebula per unit time is equal to the total number
of ionizing photons. Secondly, we need to assume thermal equilibrium so that the total
number of ionizations is balanced by the total number of recaptures per unit time:

\[ \int_{\nu_0}^{\infty} \frac{L_\nu}{h\nu} d\nu = \int_0^{r_1} n_p n_e \alpha_B(H^0, T) dV, \quad (23) \]

where \( L_\nu \) is the luminosity of ionizing radiation at a certain wavelength, \( \nu_0 \) is the
Lyman limit, below which radiation will not ionize hydrogen atoms, \( n_p \) and \( n_e \) are the
proton and electron number densities, respectively, and \( \alpha_B(H^0, T) \) is the recombination
coefficient including ionization processes due to diffuse ionizing photons emitted in re-
captures within the nebula. We can combine this equation with the luminosity of the
entire nebula in a particular emission line, for example \( H\beta \), to find

\[ \frac{L(H\beta)_{\nu_0}}{L(H\beta)_{\nu_1}} = \frac{\int_0^{r_1} n_p n_e \alpha_{\text{eff}}^{H\beta}(H^0, T) dV}{\int_0^{r_1} n_p n_e \alpha_B(H^0, T) dV} \approx \frac{\alpha_{\text{eff}}^{H\beta}(H^0, T)}{\alpha_B(H^0, T)}. \quad (24) \]

One important conclusion from this equation is the fact that the number of photons
emitted by the nebula in a specific recombination line is directly proportional to the
number of photons emitted by the star with \( \nu \geq \nu_0 \). This proportionality is indepen-
dent of any assumption of the density law in the medium, and only weakly depends on
temperature. Furthermore, in principle any recombination line can be used, as well as a
radio continuum measurement at any frequency where the nebula is optically thin.

Finally, we can compare the number of ionizing photons to the luminosity of the star
at a particular frequency \( \nu_f \) in the observable spectrum:

\[ \frac{L_{\nu_f}}{\int_{\nu_0}^{\infty} \frac{L_\nu}{h\nu} d\nu} = \frac{h\nu_f}{\alpha_{\text{eff}}^{H\beta}(H^0, T) \pi F_{\nu_f}}. \quad (25) \]

where the ratio of luminosities is expressed in terms of the ratio of observed fluxes from
the star at \( \nu_f \) and from the nebula at \( H\beta \). Note that this ratio is independent of distance
and interstellar extinction if the nebula and the star are observed at the same effective
wavelength \( \nu_f = \nu_{H\beta} \). Here again, any observable frequency \( \nu_f \) can be used, as well as
any recombination line. For looking at stars in bright nebulae, it is advantageous to
use a narrow-band filter that isolates the stellar continuum while avoiding the brightest
nebular emission lines. Assuming that the stellar flux is accurately represented by a black
body spectrum, one can replace \( L_\nu = B_\nu(T_s) \), i.e. a Planck function with a particular
temperature \( T_s \), the so-called Zanstra temperature. However, stellar continua are known
not to be represented accurately by blackbody spectra, and the correspondence holds
for the more complicated spectra of X-ray binaries even less. For the analysis presented
in the later parts of this thesis, the Zanstra temperature is therefore a concept that does
not have much predictive value.

It is important to note that this analysis is based on a very basic assumption: that
all radiation in the nebula in a certain wavelength range - the ultraviolet - is completely
absorbed in the nebula. This, however, must not necessarily be true if the HII region is not bounded by an ionization front, but by a density change. Then the medium may become optically thin to ionizing radiation before this radiation has been fully reprocessed into optical and infrared emission, and hence still be visible. Equation 25 may then be modified into

\[
\frac{L_\nu}{\int_{\nu_0}^{\infty} L_{\nu_0} d\nu} = \eta_H \frac{\alpha_{\text{HII}}(H_0, T)}{\alpha_B(H_0, T)} \frac{\pi F_\nu}{\pi F_{\nu_{\text{HII}}}} \tag{26}
\]

where \(\eta_H\) is the fraction of hydrogen-ionizing photons that are absorbed in the nebula.

4 The Environment Around X-ray binaries

Strömgren’s original assumptions rely on an isotropic medium with a constant density (Strömgren, 1939). However, in real-life situations this assumption is not valid, since especially HMXBs can be in rather complex, star-forming environments (Zezas, 2006): in order for a binary to consist of a compact object and a massive companion, the progenitor must have evolved on a very rapid timescale. Thus HMXBs are often young and cannot have moved too far from their original birth place. The supernova explosion that created the black hole carves out a large-scale, low-density cavity that the X-ray binary may be located in, unless it is old and has a high space velocity. Finally, the evolution of close-by stars and other objects - molecular clouds, HII regions of massive stars, stellar winds - may all impact the environment around an XRB, and consequently what the density and abundance structure of material is that radiation passes through. The situation is different for LMXBs, which can be old and sometimes are found to have moved a long distance through the galaxy (e.g. Mirabel et al., 2001). Therefore, LMXBs are potentially in much simpler environments.

In a recent paper by Hao & Zhang (2009), the authors explore the environment around the black hole X-ray transient XTE J1550-564 as well as another XRB system, H 1743-322. They examine eight Chandra X-ray observations of XTE J1550-564 and track the motion of the jet lobes through time. Subsequently, they assume that the kinematic and light-curve evolution can be understood as the interaction between outburst ejecta and the ISM, and fit a kinematic jet model. They find that modeling the eastern jet of XTE J1550-564 is possible while assuming a constant number density in the medium the jet travels through. However, for the western jet, this is not possible: the western jet had travelled by 2002 as far as the eastern jet had travelled by 2000, but was decelerated much more significantly. This deceleration requires a much stronger interaction, and thus higher densities. There is, however, one problem: if the number density is not high enough, the jet will not decelerate sufficiently to similar velocities as seen in the observations, and be much larger than observed. If the number density is increased to a hundred or a thousand times the generic ISM density (1 particle per cubic centimetre), then the jet never reaches the distance it reached in the observation. One may increase the jet energy, but then even a number density a hundredfold that of the generic ISM
densities will not decelerate the jet. This realization led the authors to postulate that
the environment around the XRB is not uniform, but that the system is embedded in a
large-scale cavity, where the density is significantly lower than that of the surrounding
medium. They subsequently fit both jets in conjunction with a model that involves
a cavity with ISM densities of roughly $10^{-3}$ cm$^{-3}$, and a cavity radius on the sky of
16 arcsec.

They propose to unify the different observations of small jets, large-scale jets and even
larger jet relics into a consistent picture of jet-interaction with the environment: if the
jet travels through a cavity, then the small-scale jets observed in some X-ray binaries
during outburst are essentially jets in free expansion through a thin medium. Radiation
is observed from synchrotron emission of fast-moving jet particles. Small-scale jets are
visible for typically only a few tens of days. If they hit the cave boundary, interaction
between jet material and the denser ISM may reheat particles. The jet will become
visible again as large-scale jets when it hits the cavity boundary. In this medium, the
jet will slowly expand as it lost most of its kinetic energy in the boundary, and carve out
a large-scale bubble that expands slowly into the interstellar medium, while sweeping
up ISM material. This process can be seen in the large-scale, virtually unmoving relics
that are often observed as diffuse structures in radio, optical and X-ray images, or as
unmoving rings or nebulae.

In practice several states are observed in X-ray binaries. In Cygnus X-1, for example,
large-scale jet relics are observed at the same time as small-scale jets. The authors do
note that it is unknown how these cavities are created, or indeed if they are spherical.
It is possible that a previous jet ejection event created a tunnel-like cavity in the jet emis-
sion direction through which a subsequently emitted jet may pass. Spherical cavities,
on the other hand, may be created by a multitude of processes: stellar winds and jets,
supernova explosions and previous outbursts.

Observational evidence for HII regions around X-ray binaries is relatively scarce. This
is in part due to the fact that all known black hole binaries except for a few are located in
the galaxy in relatively low-density environments so that the emission will be too diffuse
to be picked up by a telescope on Earth. A similar argument has been used to explain
why there are only very few examples of radio lobes, a typical AGN feature, observed
around microquasars. Heinz (2002) argues that in a dynamical sense, microquasars are
in less dense, less pressurized environments than AGN (although the actual hydrogen
number densities are higher in the ISM than in the inter-galactic medium). Consequently,
their surface brightness is much smaller than for AGN, and they are harder to observe.

For the reasons presented above, It is not surprising that the best evidence for a pho-
toionized nebula around a black hole source is LMC X-1, where Pakull & Angebault
(1986) found evidence for extended $\lambda$4686Å line radiation that points to photoionized
HeIII. The extent of diffuse HeIII emission is 24 arcsec, corresponding to 6 pc at the
currently inferred distance of the LMC. The authors point out that the formation and
recombination of doubly ionized helium requires a substantial intensity of helium-ionizing
photons at energies $E_{\text{phot}} \geq 54$ eV, which cannot be provided by even the hottest O-
stars. They hence conclude that this kind of emission is likely produced by a source bright in strong X-rays, consistent with an X-ray binary.

More recently, another type of source has sparked the interest of the astrophysical community: ultraluminous X-ray sources (ULXs). These are extragalactic sources that are extraordinarily bright in X-rays, with several explanations proposed for their high X-ray luminosity. They could either be stellar-mass black holes accreting at super-Eddington rates, or alternatively emit radiation that is strongly beamed towards us. Another explanation assumes they contain intermediate-mass black holes. Because they are so bright, and at the same time very far away, it is possible to see and resolve bright optical nebulae around the central X-ray-emitting source (Pakull & Mirioni, 2003). In recent years, many of these nebulae have been found in narrow-band observations of transitions of ionized helium, as well as forbidden line emission of other elements with higher stages of ionizations, like [OIV] (e.g. Berghea et al., 2010).

The best evidence for a region heated by emission from an XRB in our galaxy comes from the infrared imaging observations with ISOCAM presented in (Mirabel et al., 1996a) and reiterated in Section 2.5.1 above. The presence of a warm dust component indicates that there is some level of interaction between the source and its environment, although it is yet to be seen if a similar HeIII structure as seen in extragalactic sources can be detected for galactic black hole binaries.

5 Cloudy

Cloudy is a freely available, C++-based photoionization code designed to perform radiative transfer calculations through a cloud surrounding an ionizing source. It was first created in Cambridge in 1978 by Gary Ferland, and its first versions were written in FORTRAN\(^1\). Porting to the more modern C++ programming language was done during the mid-1990s, but FORTRAN-compatibilities have been maintained. The code currently involves over 200,000 lines of code, and incorporates large databases of atomic, molecular and dust grain properties, as well as a large compilation of stellar atmosphere models. The major long-term goal of the simulation is to simulate broad-line regions of quasars, but in more recent years, there has been some emphasis on the modeling of galactic nebulae as well.

In order to run the code, a set of initial condition is specified by the user via a number of basic input parameters, which are given to Cloudy in form of a plain ASCII script; Cloudy will subsequently compute radiative transfer, physical conditions in the cloud as well as the resulting spectrum and line emissivities in the outwards direction for radial shells of varying thickness. This integration is done out to a user-specified radius, most commonly the edge of the ionized cloud. In the following, I will show how to create an input file and what kind of output Cloudy produces. Further details of the code and its

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\(^1\)Details about the implementation and history of Cloudy can be found on the following website: http://www.nublado.org
parameters can be found in the most recent publication on the code in Ferland et al. (1998), or in the extensive documentation distributed with the code, called Hazy.

5.1 Defining a Model

Defining a model in Cloudy is done in a simple text file containing a list of parameters and commands for Cloudy to take into account. This data file is called together with Cloudy, which then uses the parameters stored in the input file to create a model of the resulting cloud. Several quantities have to be specified to enable Cloudy to create a model:

- the shape and brightness of the radiation field striking the cloud
- the initial hydrogen density
- the composition of the gas and whether dust grains are present
- the thickness of the cloud

There is a multitude of additional parameters that will specify a model more precisely. I will in the following introduce the most important commands that I have used in this project.

5.1.1 The Input Spectrum

Defining the input continuum shape and strength correctly is vital, since the incident radiation field determines the conditions in the gas very strongly. There are several pre-defined continuum shapes for common astrophysical objects and radiative processes, for example a blackbody spectrum, bremsstrahlung and cosmic microwave background emission. Combinations of different shapes are possible to create a total incident continuum. The \texttt{interpolate} command enables the user to input a custom spectral shape. This is what has been used throughout this work. Note that the individual numbers that define the spectral shape are unitless and are taken as relative strengths of the continuum at that frequency. Rather than using the unit frequency, the energy unit Rydberg, defined as 1Ryd = 13.6eV, is used by default in Cloudy. This sets the ionization edge in the spectrum at a value of 1 Ryd. Consequently, the shape of the incident spectrum is put into Cloudy in pairs of (energy in Rydberg, unitless relative continuum).

The total strength of the incident continuum can be defined in several different ways, as luminosity, intensity, ionization parameter, energy density and several others. Since luminosity presented itself as the most straightforward way to describe the strength of the incident continuum in Cloudy, it was used throughout this work. If it is defined as a luminosity, the spectral output of Cloudy, e.g. the continuum and line strengths, will be in units of erg s$^{-1}$cm$^{-2}$, or in physical quantities $\nu L_\nu / 4\pi r_0^2$, where $\nu$ is the frequency, $L_\nu$ the monochromatic luminosity at this frequency, and $r_0$ is the distance from the central object to the inner edge of the cloud. If the total continuum strength is defined as an
intensity, then the spectral output will have the same units as in the luminosity case, but be defined as $4\pi\nu J_\nu$, where $J_\nu$ is the intensity.

5.1.2 Basic Geometry

![Open Geometry vs Closed Geometry](image)

Figure 7: Examples of geometric considerations in Cloudy. Left: an open geometry, with a slab-like nebula between the illuminating source and the observer. Right: closed, spherical geometry, where light from the far side of the nebula may be reflected and scattered into the line of sight. The left diagram also illustrates the concept of inner and outer radius as well as thickness. Taken from Cloudy’s documentation Hazy, distributed with the code.

Defining an appropriate geometry is of crucial importance for a valid Cloudy model. On the most basic level, Cloudy distinguishes between a plane-parallel and a spherical geometry (see Figure 7 for an illustration). The difference between the two is in how reflected emission is treated: in a plane-parallel nebula (Figure 7, left sketch), it is assumed that the emission enters the cloud on one side and a combination of transmitted, scattered and emitted radiation leaves the cloud on the other side. In a spherical geometry (Figure 7, right sketch), radiation may hit the far side of the cloud, i.e. the part of the cloud that is behind the object in our line of sight, and be reflected there. The radiation on the incident face of the cloud therefore has an additional component due to this reflected emission (see also Figure 8 below). A special case that is also possible is a cylindrical geometry: this is a spherically symmetric model in principle, but the nebula is truncated on two ends to simulate a cylinder.
Several other parameters affect the geometry of the simulation: the distance, covering factor, filling factor, inner and outer radius, as well as the aperture size.

The distance command sets the distance of the object to Earth. This parameter is important if line-emission fluxes on Earth should be predicted. It is also valuable if combined with the aperture command, which can be used to set different observation cases: in general, Cloudy computes the spectrum of the object from a pencil beam leaving the cloud. This treatment, however, differs for line-emission fluxes. These are, as per standard, integrated over the whole nebula, according to the equation for an observed quantity $Q_\alpha$

$$Q_\alpha(\lambda) \propto \int \left(\frac{r}{r_0}\right)^\alpha \epsilon(\lambda)dr ,$$

where $\epsilon(\lambda)$ is the line’s volume emissivity at wavelength $\lambda$, $r_0$ is the inner radius of the cloud, i.e. the distance from the central object to the face of the cloud, and $\alpha$ describes the different aperture cases: for $\alpha = 2$, this equation calculates the line fluxes integrated over the whole nebula; for $\alpha = 1$, a long-slit case is described, where the line-emission flux is calculated for a long, thin section of the nebula. Finally, $\alpha = 0$ describes the case of a pencil beam through the centre of the nebula. Note that these considerations are only important in the luminosity case; in the intensity case, where no inner radius is set, all calculations are for a pencil beam through a slab. Finally, it must be stressed that this only affects line emissivities that can be output in a file. The overall spectrum, including transmitted and diffuse continuum emission, is always the spectrum of a pencil beam through the centre of the nebula.

In some situations, the illuminating object may not be embedded in a nebula, but we might be interested in a nebula between us and the source. In this case, the standard geometries of an infinite slab or a spherical nebula around the source are not valid representations of reality. In these cases, one may set a covering factor $\Omega/4\pi$. This parameter sets the fraction of the sky covered by the cloud with respect to the source, and affects both the luminosity of the emitted spectrum as well as radiative transfer of line and continua. In the luminosity case, all luminosities will be computed for a shell covering $\Omega sr$ of the central object, and line luminosities scale almost linearly with the covering factor. In the intensity case, only second-order effects will influence the spectrum, since in this case, emission per unit area of the cloud is considered.

In the luminosity case, an inner radius has to be set. This inner radius is the distance from the central object to the inner surface of the cloud and is necessary to calculate the monochromatic luminosities at the incident side of the cloud. An outer radius can be set to specify where the simulation stops, or, alternatively a thickness. This is, however, optional, and there are many other valid stopping criteria described in Section 5.1.4 below.
5.1.3 Defining the Environment

For Cloudy to do an accurate radiative transfer simulation, it needs to know very precisely what kind of environment the light from the central sources passes through: the hydrogen density at the inner face of the cloud, some sort of equation of state or density law, as well as abundances need to be known in order to calculate the physical conditions in the medium. An initial hydrogen density must always be set. This is done with the command \texttt{hden \, x}, where \texttt{x} is the logarithm of a number. As a default, Cloudy assumes the density is constant throughout the cloud. This can be changed by explicitly specifying a density law: modifying the command to \texttt{hden \, 2, power=-2}, for example, will set a hydrogen density at the face of the cloud of $10^{2}\text{cm}^{-3}$, falling off with a power-law with index $-2$. Cloudy can also solve basic gas equations, in order to calculate other density and temperature laws. For example, the command \texttt{constant pressure set 5} holds the total pressure, the sum of gas pressure, radiation pressure, as well as pressure due to lines, turbulence and magnetic fields, constant. Similarly, the gas pressure can be held constant using the command \texttt{constant gas pressure}; this specifies an isobaric density law

$$P_{\text{gas}} = n_{\text{tot}}kT_{e}$$

where $n_{\text{tot}}$ is the total particle density and $P_{\text{gas}}$ is kept constant. Finally, it is possible to introduce a user-specified density law using the \texttt{dlaw}-command and a user-written file containing the density law.

Besides the hydrogen density and density laws, an important set of parameters pertains the chemical composition of the medium surrounding the central source, i.e. the abundances of elements in gas phase as well as dust grains. There are several sets of abundances for 30 of the most important elements stored in Cloudy, corresponding to well-known and common situations. The default abundance set used are solar abundances coming from various sources (Allende Prieto et al., 2001, 2002; Holweger, 2001; Grevesse & Sauval, 1998). Abundances are always specified by number relative to hydrogen, not by mass. Abundances are also always specified relative to the total number of hydrogen atoms found in atomic, ionic and molecular form. Note that these and the abundances of other elements do not include atoms locked in dust grains and ices. The chemical composition can be modified either in its entirety or separately for single elements. In order to change one composition, say, for a nebula depleted in helium, one may use the command \texttt{element scale factor helium 0.1}. For this simulation, the amount of helium will be scaled down by a factor of 0.1 as compared to the original set of abundances. There are several additional abundance sets stored in Cloudy. They specify abundances for an HII region (the subjective mean of the Orion Nebula abundances), a planetary nebula, the ISM, a nova (for the classical nova V1500 Cygni), the primordial abundances (all elements except helium, lithium and beryllium are set to zero). The abundance sets for the ISM, planetary nebulae and HII regions also contain depletion of gas phase elements onto grains. For other compositions, grain chemistry can be added using the \texttt{grains} command, combined with a keyword specifying grains for different grain abundance patterns and size distributions, most notably ISM-type dust grains as
found in our galaxy, Orion nebula-type grains and PAH chemistry.

5.1.4 Stopping Criteria

Just as it is important to set appropriate starting conditions for a simulation, it is crucial to know how and why a simulation ends. This is particularly important because many outcomes, such as a predicted emission-line spectrum, depend strongly on the thickness of the cloud.

There are two general geometries: a radiation-bounded nebula is one where the outer edge of the emitting gas is a hydrogen ionization front. In other words, this nebula has an outer boundary defined by the ionization of hydrogen dropping below a minimum value. Often, 5% is used as a somewhat arbitrary definition. This occurs at an electron temperature at about 4000K for ionization/recombination events that result in optical emission lines. Since the material behind the ionization front is hotter and ionized, the ionization front is expected to expand into the ambient medium as a shock wave, stopping only when hydrostatic and thermal equilibrium is reached. Therefore, time-independent simulations are intrinsically unrealistic, except when the nebula is very old. Radiation-bounded geometries can be realized with various stopping commands: stop temperature for example lets the user specify a lower temperature limit. The simulation will stop when the electron temperature reaches this limit. Other commands are stop eden and stop efrac, which stop the simulation when a certain lower limit in the electron density or electron fraction - the ratio of electron to total hydrogen density - is reached.

In a matter-bounded geometry, on the other hand, the gas is optically thin to energetic radiation and an outer radius of the cloud must be specified in some way. This is often done using a physical thickness of the cloud, using the radius command described in the previous section. Alternatively, the stop mass command stops the simulation when the cloud has reached a specified mass, and the stop column density command stops the simulation when a certain column density has been reached.

Several other commands are available for stopping the simulation; those mentioned above present a summary of the ones most commonly used.

5.2 Output

The Cloudy code produces a large amount of data which can be accessed in various ways. All results, together with valuable information about the simulation, errors and cautions, are saved in an output file. This file, however, is relatively unordered and not usable with common plotting programmes. The punch (deprecated in the coming version C10.0 of Cloudy, where it has been renamed to save) offers a valuable alternative: allows the user to access different parts of the data and store them in separate files accessible by plotting programmes. The command punch continuum in its various forms creates a file with spectral data. The incident spectrum, as well as several components and the total outward spectrum is saved, together with photon energies in Rydberg (the
Figure 8: Illustration of the different components that contribute to the total outward spectrum. Taken from Cloudy’s documentation Hazy, distributed with the code.

different components that can be found in the continuum output - incident, transmitted, diffuse, reflected, and the combined spectrum with all components - are shown in Figure 8). They are easily accessible by programmes like gnuplot and offer the possibility to compare for example the incident spectrum to the total outward spectrum, the spectrum of purely transmitted radiation and the spectrum of purely diffuse, nebular emission.

Cloudy can do more, however. Its radiative transfer code also calculates several physical parameters of the cloud: using the punch overview command, it is possible to track physical conditions like the total pressure, hydrogen density and temperature throughout the cloud, as well as the ionization structure. This is especially important when investigating whether a simulation is physical. Many other parameters may be accessed this way, such as dust grain properties, various elemental abundances, photoionization rates, emission line data, opacities and pressure. In this work, the most important output comes from the punch continuum and punch overview commands.

5.3 A Note on C08.00 vs. C10.00

During the research period for this thesis, a new version of Cloudy was prepared to be released. At the time of writing, Cloudy C10.00 is not a full release version, but a publicly available test version in which errors are constantly fixed. We have used it, however, for much of this work, as the stable release version C08.00 has several numerical errors that cause the simulation to crash for some of our specified initial conditions. Many of these bugs are fixed in C10.00. There is only one major difference in syntax between both versions, which is the introduction of the command save, making punch obsolete. Since Cloudy is backward compatible, punch can still be used in the new version, and C08.00 syntax has been used consistently throughout this thesis in order to keep scripts
6 Modelling Cygnus X-1

Cygnus X-1 was chosen for this work as a calibration source. While our ultimate goal is to constrain the UV flux in order to distinguish between different models for the region close to the black hole, it is imperative that we first develop a simulation of the environment around an XRB that is physically valid. Cygnus X-1 has two advantages: as a HMXB, its UV spectrum is dominated by the stellar blackbody of the companion. Since this type of spectrum is very well known, we essentially have a very good idea what the UV flux in Cygnus X-1 looks like. We can base our model purely on the observed fluxes at different wavelengths, and no model assumptions about the emission regions of these fluxes are made. Therefore, it is useful as a calibration source for our Cloudy model when exploring what effects the UV emission has on the interstellar medium, and how the interstellar medium in turn reprocesses the UV radiation to longer wavelengths. Additionally, it is a persistent source that is often found in a fairly stable hard-like state. It has been extensively monitored, and its behaviour in the LHS is thus comparatively well-understood. For this reason, it is possible to compile a broadband spectrum from non-simultaneous observations that is more detailed and complete than for any other black hole binary and nevertheless reasonable for the kind of preliminary analysis attempted here. It should be noted, however, that the non-simultaneous nature is a limitation on the validity of predictions made.

6.1 Input Spectrum

![Figure 9: Broadband spectrum of Cygnus X-1, from Tigelaar and Fender (private communication).]

The input spectrum, shown in Figure 9 is a combined spectrum that draws from several observations all across the electromagnetic spectrum (Tigelaar & Fender, private communication).
communication). The overall spectrum is dominated by a flat component at low energies that is interpreted as jet emission, as well as a blackbody component peaking at UV wavelengths. This is presumably emission from the O9.7 Iab black hole companion star. The total luminosity of Cygnus X-1 is calculated by transforming measurement values from milliJansky to monochromatic luminosities, assuming a distance of 2 kpc (Massey et al., 1995). Subsequently, the total luminosity is calculated by integrating over all given data points, using both left and right Riemann sums. The final luminosity used is the average between left and right sums, and found to be about $4 \times 10^{39}$ erg s$^{-1}$, in good agreement with estimates found in the literature (Ziolkowski, 2005). The Riemann sums were done using a simple python script, which can be found in Appendix B. Since for the spectrum itself only relative differences between data points matter, it does not make any difference in which units the values are in. However, the corresponding energy needs to be specified in Rydberg. Therefore, frequencies were converted into Rydberg using the appropriate conversion factors. The input spectrum used in the appropriate units can be found as part of the example script in Appendix A.

6.2 Exploring Parameter Space

I explored parameter space, particularly the environmental parameters, for two main reasons: first, the details of the environment around X-ray binaries are fairly poorly constrained, and second, I was interested in the behaviour of the code in different parameter regimes, to find out what is physical and what is not. Thus, I implemented different density laws, different hydrogen densities and dust depletion factors, as well as different stopping criteria to see how the final spectrum would be affected. In every case, all other parameters are kept the same, in order to be able to compare the models directly. Stopping criteria vary between models, but in most cases the simulation is stopped when the electron temperature of the gas reached 4000K. This temperature roughly coincides with the edge of a radiation-bounded nebula, and was used in order to simulate the full development of an HII region. In practice, the edge of an HII region can be as far as tens or even hundreds of parsecs, and it is very unlikely to find a medium undisturbed by any other gas clouds, stars or other objects on these scales, thus this is not strictly very physical. It merely serves to illustrate the full structure of an HII region. For the constant-density region, this choice of stopping criterion does not make sense, since for a higher number density, the Strömgren sphere will be smaller, and in effect the amount of material the radiation passes through will still be the same. These simulations were stopped at a fixed radius that was the same for all models in these tests. In Section 5.1.4, the stopping parameter itself is varied, and obviously a temperature-limit does not make sense in the constant-temperature model, since the limit can never be reached.

The results turn out to be somewhat ambiguous: different combinations of parameters all give results that may be considered physical and fit the observed spectrum. Further observations, especially in the optical, may yield more robust constraints as to which set of parameters is appropriate.
6.2.1 Density Laws

One fundamental decision that needs to be made is which density law should be used. The term ‘density law’ here is not directly restricted to the definition of the density structure of the cloud, but rather encompasses all commands that in some way determine what the structure of the cloud will look like and are connected via an equation of state. To get a basic idea, I ran three models with different density laws: constant density, constant pressure and constant temperature. In the first case, the hydrogen number density is held constant throughout the cloud, this is the default density law in Cloudy. The second model describes a nebula in hydrostatic equilibrium, where the total pressure is kept constant:

\[ P_{\text{tot}}(r) = P_{\text{tot}}(r_0) + \int a_{\text{rad}} \rho dr = P_{\text{gas}} + P_{\text{lines}} + P_{\text{continuum}}. \]

Here, \( P_{\text{tot}} \) is the total pressure and constant for hydrostatic equilibrium, \( P_{\text{tot}}(r_0) \) is the total pressure at the inner face of the cloud (at \( r_0 \)), \( a_{\text{rad}} \) is the radiative acceleration at position \( r \) in the cloud, \( P_{\text{gas}} = n_{\text{tot}} kT \) is the thermal gas pressure, and \( P_{\text{continuum}} \) and \( P_{\text{lines}} \) are the radiation pressures due to continuum and line radiation, respectively. If the simulation includes turbulence, magnetic fields or stellar winds, the various pressure terms due to these phenomena need to be taken into account as well.

Finally, the third model keeps the electron temperature constant, but lets pressure and hydrogen density free to vary. Of all three models tested, this is the one most unlikely to be realistic, for the following reason: the emission heating the nebula is emitted more or less spherically symmetric by a central source, and hence falls off with distance with the usual \( \propto r^{-2} \) proportionality. As we move away from the source through the cloud, there is less and less radiative energy available per unit surface to heat the cloud, thus one would intuitively expect the temperature to drop with distance in the cloud, unless there are radiative sources replenishing the energy available for heating the cloud at every spot in the nebula. This negative dependence of temperature with radius is indeed observed in every other model (see Figure 10), and thus the constant-temperature model was disregarded as unphysical in the rest of the analysis.

We can draw several conclusions about the models from the temperature structure of the different model nebulae presented in Figure 10. The initial temperature in the nebula is very high, due to the extremely high luminosity of the central source, especially by the O-star companion supplying the overwhelming majority of the ionizing photons in the UV and X-ray part of the spectrum. These photons ionize hydrogen, helium and heavier elements close to the source. The resulting free electrons have high kinetic energies. Secondly, for both the constant-density and the constant-pressure simulation, the temperature remains very high over several orders of magnitude in distance out to a radius of \( 10^{17} \) cm in the constant-density case, and \( 10^{19} \) cm in the constant-pressure case. At these high temperatures near the central source, the medium is hot enough to be completely optically thin to the incoming radiation, as the material is largely ionized in both hydrogen and helium. Because electrons are so hot, any recombination will likely
Figure 10: Testing different density laws for Cygnus X-1: electron temperature structure of the modelled HII region. In green, the constant temperature model, in red, the constant density model, and in blue, the hydrostatic equilibrium model.
produce a photon with a frequency high enough to produce another ionization. Only when the radiation has thinned out sufficiently is it possible to have recombinations producing lower-frequency photons that can escape the nebula. At this point, heat is lost from the cloud in the form of outgoing radiation at wavelengths where the neutral material is optically thin, and the temperature drops. Note the jump in the constant-pressure model (in green). According to the log-file of this simulation, temperature, ionization of several elements and hydrogen density jumped by at least an order of magnitude at this zone in the code due to numerical integration problems. This is obviously not physically valid, and this simulation should hence be interpreted only cautiously.

Figure 11: Testing different density laws for Cygnus X-1: hydrogen number density structure of the modelled HII region. In green, the constant temperature model, in red, the constant density model, and in blue, the hydrostatic equilibrium model.

The same jump can be seen in the density structure, Figure 11 (in blue). For the constant-pressure model, the hydrogen density structure of the cloud mirrors the behaviour of the electron temperature: as soon as the temperature begins to drop, the hydrogen density increases in order to keep the pressure constant. Note that the initial hydrogen density is $10^{-6} \text{ cm}^{-3}$, far below the typical ISM values, and therefore probably not physically valid, but explains why the high-temperature part of the nebula in
the constant-pressure approach is about two orders of magnitude larger than for the
constant-density approach: because the medium has such a low hydrogen density, there
is not much radiative transfer happening out to where the density is higher. For both
the constant-density and the constant-temperature simulations, the hydrogen number
density remains constant. For the former, this is set artificially, for the latter, it is an
outcome of the model, and probably due to the fact that with the temperature unchang-
ing, the ionization state does not change much either, and the difference due to the
decreasing irradiation with radius is compensated by the fact that the pressure does not
need to be constant.

6.2.2 Hydrogen Density

The importance of the initial hydrogen density depends strongly on the density law used.
It is most important, obviously, for a constant-density model, since it then - together
with the stopping criteria - determines how much matter the central source’s radiation
would go through, and thus how much emission can be reprocessed into line and con-
tinuum emission. For hydrostatic equilibrium, the situation is trickier, since in some
of these models, with extreme pressure conditions e.g. due to extremely high radiation
pressure, the code will forcibly set a new hydrogen number density to ensure hydro-
static equilibrium within physically possible temperature bounds set within the code.
For constant-pressure models, as the temperature decreases, the density must go up in
order to keep the gas pressure roughly constant. This is reflected in Figure 11.

The for a constant-density model, the impact of the hydrogen number density on the
resulting model spectrum is plotted in Figure 12. The higher the density of the nebula
material, the more emission can be reprocessed up to the edge of the nebula because the
chance of interactions between photons and atoms as well as free electrons and ions is
higher. Hence, line emission will be stronger for models incorporating a higher density,
and continuum emission from free-free emission processes dominate the radio and far-
infrared wavebands. There is a prominent dip in the UV spectrum for models with high
hydrogen number density, which is the source of photons for reprocessing. The dip is
necessarily smaller for smaller number densities, since less emission is reprocessed in this
case.

6.2.3 Stopping Criteria

One of the most important decisions to make when choosing parameters for a Cloudy
model is how and when the simulation is supposed to stop. This decision has a great
influence on what the final spectrum will look like, and not always does a simulation stop
for the reason it was intended to stop. For example, Cloudy may stop the simulation
when the size of an individual integration step gets too small, or when the maximum
number of integration steps set within the code is reached. When the radiation pressure
is higher than the gas pressure, the simulation will abort as well and produce an error
message. The code’s output should be checked carefully to ensure the simulation stopped
Figure 12: Testing different hydrogen densities for Cygnus X-1: effect of different hydrogen densities on the spectrum.
for the reason defined in the input script. The most fundamental choice is whether the HII region is radiation- or matter-bounded. In the former case, one would want to chose a stopping criterion that reflects the physical conditions at the ionization front, e.g. a low ionization parameter, or a gas temperature of about 4000 K. In the second case, where the cloud ends for some other reason, it makes more sense to choose a stopping criterion like an outer radius (if one is known) or a column density.

Figure 13: The effect of different stopping column densities on the resulting model spectrum.

For either choice in a matter-bounded nebula, the effect on the model spectrum is the same and in both cases similar to the what happens when the density is varied. Since varying the stopping radius effectively translates to varying the amount of material the radiation passes through, this is not surprising. In Figure 13, I show the effect of choosing different values for the stopping criterion, in this case a hydrogen column density, on the resulting model spectrum. The higher the column density, i.e. the more material the radiation passes through, the stronger the line and free-free radiation in the resulting model spectrum.
6.2.4 Dust

The question of whether or not there is dust in the medium around the X-ray binary is an important one, and one that is not easy to answer. The interstellar medium does contain copious amounts of dust; however, it strongly depends on the kind of environment the XRB is in for that to be true there as well. Cygnus X-1 is supposedly the member of a relatively young OB-association, with much star formation and stellar evolution on rapid time scales due to the massive stars involved. Additionally, the stellar-evolution history of Cygnus X-1’s binary components is likely to affect the medium around them: the supernova explosion that created the black hole - even if it was relatively quiet as suggested in (Mirabel & Rodrigues, 2003) - has blown out material that sent a shock wave through the interstellar medium. As Cygnus X-1 has moved around 60 pc from the projected centre of the OB-association assuming the estimates of age and distance are correct, it is unlikely, but not impossible that Cygnus X-1 is still within the bounds of its remnant. No supernova remnant has so far been associated with the source. The stellar wind of the young high-mass companion HD226868 is presumed to be strongly focussed on the black hole companion. Even so, only a fraction of material ejected by the companion is accreted by the black hole. A fast stellar wind as is typical for an O-star blows out a cavity of the order of several parsecs around itself. Within this shock-blown bubble, all dust should be destroyed.

Both Persi et al. (1980) and Mirabel et al. (1996a) (infrared data in Figure 14) measured an infrared excess that the authors of latter paper attributed to a warm dust component, and the authors of former paper attributed to free-free as well as bound-free emission from the stellar wind. Either possibility is hard to test with Cloudy, since both infrared observations were done integrating over a reasonably large area (about 5 by 5 arcseconds in Persi et al. (1980) and 6 by 6 arcseconds in Mirabel et al. (1996a)). Therefore, any results in Cloudy will not be comparable, since the Cloudy spectrum only represents a pencil beam through the centre of the nebula. It is, however, the case that the infrared excess above the stellar continuum seems to have a bump, and the ISOCAM data shown in Figure 14 coincides with the stellar blackbody spectrum. Comparing this to the spectra shown above in the sections exploring the hydrogen density and stopping parameter (see Figures 12 and 13), where free-free emission dominates the infrared and radio part of the spectrum for some simulations, it can be concluded that this behaviour is uncharacteristic for free-free emission: the free-free excess in these models does not decrease with longer wavelengths; the contrary is the case: the free-free excess increases with wavelength. Thus, it is rather more likely that the infrared excess is indeed rather due to dust grains than to free-free emission. This conclusion should be taken with a grain of salt, however: Mirabel et al. (1996a) do not describe their observational procedure in detail, in particular it remains unclear which steps have been taken to correct the observations for interstellar radiation during the data preparation process. It is hence possible that part of the emission from the nebula was subtracted out of the images before calculation of the infrared flux at long wavelengths. A similar argument holds for the IRAM observations, as described in (Fender et al., 2000) and shown in Figure 14: they were taken in position switching mode, where observations of the source were
alternated with observations at a position of about $-1\text{arcmin}$ in RA in order to subtract out environmental effects. $1\text{arcmin}$ at a distance of roughly $2\text{kpc}$ is possibly still within the limits of the photoionized region around the source, hence emission of gas and dust around the source would effectively be subtracted out.

I can nevertheless estimate the effect of dust on the system. The strength of dust emission in the model crucially depends on the dust abundance within the system, as compared to the gas densities. In order to explore the effect of dust on the spectrum, I ran several models with varying dust abundances, keeping all other parameters constant. As a stopping parameter, I arbitrarily chose a column density of $10^{19} \text{cm}$. The full set of parameters is summarised in Table 1.

The effect of varying dust grain abundances is clearly visible in Figure 15: the higher the dust abundances are, the more thermal radiation is produced by dust grains. The shape of the dust grains deviates from the typical blackbody shape, but is a typical
Table 1: Model parameters for the simulations including dust grains.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>log(Luminosity) [erg s(^{-1})]</td>
<td>39.6451477</td>
</tr>
<tr>
<td>density law</td>
<td>constant density</td>
</tr>
<tr>
<td>log(hydrogen density) [cm(^{-3})]</td>
<td>1.0</td>
</tr>
<tr>
<td>Abundances</td>
<td>ISM, grain chemistry included, grain abundances varying 10(^{13})</td>
</tr>
<tr>
<td>inner radius [cm]</td>
<td>hydrogen column density (N_H = 3 \times 10^{19} \text{ cm}^{-2})</td>
</tr>
<tr>
<td>stopping criterion</td>
<td></td>
</tr>
</tbody>
</table>

Figure 15: The effect of varying dust grain abundances on the model spectrum. The dust abundances set as a dust depletion factor: 1.0 is the standard ISM case as defined within Cloudy, 0.001 Z(gas) represents the case where the dust abundances are a factor of \(10^{-3}\) smaller than typical for the ISM. The green crosses are located at the actual wavelengths at which observations are obtained. Note that there is only one observation in the part of the waveband where dust is important.
signature of the silicate component in the model dust grains (e.g. Bregman et al., 1987). The thermal blackbody can completely dominate the spectrum in the far-infrared, as is the case for the typical ISM case, without dust depletion (labelled 1 in Figure 15). Comparing the model to the observations summarized in Fender et al. (2000), I can conclude that this is very unlikely to be the case: in the model without dust depletion, there is a large infrared excess below roughly $10^{14}$ Hz. The shape of the observed spectrum between $10^{13}$ Hz and $10^{14}$ Hz seems to exclude this. The dust blackbody in the models is in general at lower frequencies than in the observations. Again, this may be true to Cloudy’s inaccuracies when treating dust grains in a relatively hot medium. Alternatively, it may be the case that the dust grain abundances and distribution patterns assumed for this model are not correct. Since Cygnus X-1 is a relatively complex region with young stellar objects, and additionally the dust grains are in a relatively harsh environment with bright X-ray radiation, a stellar wind and jets, this may significantly alter dust abundances and composition from the typical ISM values used to model the spectrum. Taking all these cautions into account, it seems most reasonable to include a small dust contribution in the model, with a dust depletion factor of of about $10^{-3}$. It should be noted that the bulk of far-infrared excess due to dust is emitted between $10^{12}$ Hz and $10^{14}$ Hz, where observations are lacking (see green crosses in Figure 15).

6.3 Looking at Individual Wavebands

In order to explore the effect of emission at different wavelengths on the total spectrum, and to see which emission processes are dominant at different wavelengths, I ran a number of models that had part of the input spectrum cut out. All physical parameters - hydrogen density, constant density law, stopping column density $N_H = 3 \times 10^{19}$ cm$^{-2}$ - of the cloud are kept constant. Only the shape of the spectrum is varied, and the luminosity is accordingly reduced such that the other components of the input spectrum retain their original flux levels.

A closer look at Figure 16 can give us many important hints as to which emission processes are important in the interstellar medium around a black-hole binary, and which parts of the input spectrum are in turn reprocessed. The material is largely optically thin except to helium ionization and heavier elements, thus the lack of X-rays in the original spectrum (Figure 16 (a), red) an effect on the resulting model spectrum (same Figure, blue spectrum) by reducing the number of X-ray excited lines observed in the infrared spectrum. Figure 16 (b), shows more emission lines in the infrared than the spectrum without X-rays, despite the fact that the UV spectrum is missing. This is surprising only on a first glance. For one, a large fraction of these lines are recombination lines either excited directly by X-rays, or through a number of ionizations and recombinations producing photons at successively lower wavelengths. Additionally, most of the energy released in Cygnus X-1 is actually released in UV photons from the companion, thus the luminosity is drastically reduced by taking out the UV part of the spectrum. Consequently, the ionization structure in this nebula differs from that of the one simulated for the whole spectrum: fewer ionizing photons equate to a smaller HII region and a lower electron temperature. This lower electron temperature is now in
Figure 16: The five models with parts of their input spectrum missing: (a) no X-ray spectrum, (b) no UV spectrum, (c) no optical spectrum, (d) no infrared spectrum, (e) no radio spectrum
the regime where radiative transfer is efficient and the nebula is optically thin to the nebular emission lines observed in the spectrum. Note, however, that the dust blackbody has vanished completely in this simulation. It can be concluded that it is mostly UV photons that excite and heat dust particles. The violet model spectrum in (b) shows some continuum radiation and numerous lines in the UV waveband, albeit mostly at much lower fluxes than the blackbody would have been. These are presumably X-ray excited lines of helium and heavy elements. A part of the flux reprocessed into UV will in turn be used to ionize hydrogen and lower ionization stages of heavier elements, giving rise to the large number of lines in the infrared part of the spectrum.

Figure 16 (c) reveals why there are no emission lines seen in Cygnus X-1 in the optical: despite the strong UV radiation, the emission line strengths remain below the optical part of the companion’s black body and are only revealed when this part of the spectrum is removed. Then a large number of recombination lines become visible. A similar argument is true for the infrared spectrum, where the companion, and at longer wavelengths the jet, dominates the spectrum. Cutting out the infrared spectrum (Figure 16 (d)) reveals the lower half of the dust-produced blackbody spectrum as well as a number of nebular emission lines, some of which are visible above the flux level where the companion/jet spectra normally would be. Many lines, however, remain below that flux level and are unobservable. Finally, the radio part of the spectrum reveals the free-free continuum hidden behind the jet. In Figure 16 (e) it becomes clear that the coincidentally free-free excess seen in Figures 12 and 13 has approximately the same flat spectrum as the jet itself. Thus, the free-free excess, if it is appreciable, only adds a roughly constant factor to the jet spectrum, but does not change the spectral slope.

6.4 The Constant Density Model

There are several constraints we can use in order to define a reasonable model:

- it is likely that there is a dust contribution in the far-infrared, as indicated by Mirabel et al. (1996a),
- the far-infrared emission imaged by Mirabel et al. (1996a) at the same time sets a minimum radius of the nebula of 0.2 pc,
- the correlation between radio and X-ray flux observed by e.g. Gleissner et al. (2004) implies that the radio spectrum is dominated by synchrotron emission from the jet and nebular free-free emission plays only a very minor role. However, Xue & Cui (2007) note that there is quite a large scatter in the correlation. This is possibly due free-free emission from the stellar wind contributing at low frequencies, or alternatively due to free-free emission from the interstellar medium. Here, we assume that a minor contribution from free-free emission from the ISM is possible, but not large enough to dominate over the synchrotron flux.

From the available constraints (possible dust contribution in far-IR, physical size of the nebula at least 0.2 pc, little free-free emission in radio), I constructed a model that
is similar to the one used in determining the role of dust in the system. I use a constant-density approach, a choice that is partly motivated by wanting to keep the model simple, but is also to some extent necessitated by the fact that simulations involving hydrostatic-equilibrium solutions tend to fail due to radiation pressure when including grain chemistry. This is mostly due to Cloudy calculating hydrostatic equilibrium and adjusting temperature and hydrogen density in the first step, the latter often to unphysically small values. For this constant-density model, I first use the constraints set in Mirabel et al. (1996a), which effectively sets an outer radius to the observed structure of roughly 0.2 pc. The hydrogen density was fixed at 10 cm$^{-3}$. This is about one order of magnitude higher than the typical value generally cited for the ISM, but accounts for the fact that Gallo et al. (2005) find the system to be in high-density environment. I include a small dust contribution as discussed in the previous section in order to account for the infrared excess. I assume a chemical composition in accordance with typical abundances of the interstellar medium, as predefined in Cloudy.

Table 2: Final set of parameters for the constant-density model for Cygnus X-1

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>log(Luminosity) [erg s$^{-1}$]</td>
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</tr>
<tr>
<td>Abundances</td>
<td>ISM, grain chemistry included</td>
</tr>
<tr>
<td>grain abundances</td>
<td>0.001 $\times$ typical ISM grain abundances</td>
</tr>
<tr>
<td>inner/outer radius [cm]</td>
<td>$10^{13}$ and $6.17 \times 10^{17}$, respectively</td>
</tr>
<tr>
<td>stopping criterion</td>
<td>outer radius set</td>
</tr>
</tbody>
</table>

The final set of parameters for this model can be found in Table 2, the total spectrum is shown in Figure 17. The total spectrum does not show any particular features except the dust emission at far-infrared wavelengths. In particular, there are no emission lines in the optical. This is expected, as emission lines are not observed, and are likely to be drowned out by the companion’s strong optical blackbody emission. Additionally, the nebula is very small, compared to the typical Strömgren radii for an object with that high a luminosity: for Cygnus X-1, the Strömgren radius is $r_s = 13.5$ pc for a hydrogen number density $n_H = 10$ cm$^{-3}$. If this is the true radius, then the HII region is unlikely to be radiation bounded, but rather matter bounded, for example via a change in hydrogen density. On the other hand, the infrared emission might not show the true extent of the nebula, for example because in the outer regions the nebular emission is too diffuse to be seen by telescopes on Earth. Thus, I implemented another model that stops at a column density $N_H = 2 \times 10^{19}$ cm$^{-2}$, allowing for a very small contribution of free-free emission to the system, but not enough for the latter process to dominate the radio emission. All other parameters equal those listed in Table 2.
Figure 17: model spectrum from the constant-density model run.
Figure 18: Same model as in Figure 17, but with a less constrained radius.
Unlike the first constant-density model, the one presented in Figure 18 shows features of line emission and absorption, as well as a prominent dust blackbody. The emission lines are particularly strong in the infrared and can be identified as recombination lines from heavier atoms such as S IV λ10.51μm, N I λ7.64μm and Mg V λ5.60μm. It is notable that there are no identifiable hydrogen emission lines in the spectrum, as well as no prominent emission lines in the optical part of the spectrum. The optical emission line spectrum is too weak to penetrate through the overwhelming emission from the companion star. In Figure 18 I also included the original observations (in green) from which the input spectrum (in red) were derived. This illustrates the lack of observations at far-infrared wavelengths, exactly the wavelength range in which imaging and spectroscopy could make a large contribution towards constraining both dust (via the continuum excess) and gas (via nebular emission lines) components of the nebular spectrum. Without these additional constraints, it is difficult to estimate the dust abundance in the system.

![Figure 19: Temperature structure for a constant-density, radiation-bounded nebula.](image)

The difference in model spectra can be interpreted when looking at the temperature and ionization structure in the nebula. Running a model almost up to the ionization front reveals the structure of the whole nebula (Figure 19 and 20). A quick look at the ionization structure for hydrogen reveals that hydrogen is completely ionized throughout
the nebula up to $10^{21}$ cm. The temperature structure shows a constant, very high ($\approx 5 \times 10^6$ K) electron temperature. Electrons with kinetic energies this high are either too fast to recombine at all, or will release high-energy photons when they do. These photons, in turn, will ionize material close-by, or escape, if the material is already ionized. Hence, up to a distance of $5 \times 10^{17}$ cm, one is unlikely to see the effects of radiative transfer in the spectrum. A bit of energy is lost in heating dust grains, which in turn emit roughly as a blackbody. These processes largely explain the lack of distinct features except dust emission in Figure 17.

**Figure 20:** Structure of ionized hydrogen and helium in the same model. He I is almost non-existent.

Figure 20 shows the ionization structure of hydrogen and helium in the HII region. Hydrogen is completely ionized out to the stopping radius of the simulation. Helium is likewise ionized up to the ionization front, making the region around Cygnus X-1 a HeII nebula, thanks to the bright companion. Additionally, the large amount of X-ray photons is able to ionize HeII in the inner part of the cloud, creating a HeIII region inside the HeII ionized zone. The outer radius of the nebula whose spectrum is shown in Figure 17 lies well within this HeIII zone, the second model with a larger outer radius roughly coincides with the boundary of the HeIII region. The high ionization states do not only ionize hydrogen and helium to a high degree, but also higher elements, whose
recombination lines are in turn seen in the spectrum. It should be noted that the models above are artificially cut off at a certain radius in the cloud. It is thus not surprising that the spectrum does not show as many features as one might expect. In reality, the situation is likely to be more complicated, even if the photoionized region around Cygnus X-1 is a relatively small, matter-bounded nebula. The boundary of the nebula seen in infrared emission may be one where the density changes. If the density drops for some reason, then the resulting nebular emission may be too diffuse to be seen with telescopes, and hence be unobservable as a large-scale structure. Nevertheless, it should be there and will influence the observed spectrum integrated along the line of sight. In that case, a more complicated model may be more accurate at modelling the actual situation.

6.5 Beyond the Simple Approach

The idea that the medium around Cygnus X-1 is of uniform density is almost certainly too simple to reflect reality accurately. Stellar winds are known to blow out low-density cavities around high-mass stars (Parker, 1961; Castor et al., 1975). Even if the wind is strongly focussed, as suggested for Cygnus X-1, only about $0.1 - 1.0\%$ of the wind are actually accreted (Gies & Bolton, 1986b), and the remainder will still escape as a high-velocity stream into the environment. The high-energy particles in this wind are likely to destroy a large fraction of dust-grain within the wind-blown cavity. The almost certainly more complex structure around a HMXB is addressed by constructing a more complicated model in Cloudy, splitting the environment in two different regimes: a wind-blown bubble where the density is roughly constant and hydrogen number density is is about $n_H \approx 10^{-1}\text{cm}^{-3}$, and a dusty outer region in hydrostatic equilibrium, where a constant pressure needs to be specified, as well as an initial density. I assume the inner region is devoid of any dust grains and the infrared excess is either due to free-free emission from the stellar wind (Persi et al., 1980), or due to dust emission originating in a halo of ionized emission at greater radii in the second zone (Mirabel et al., 1996a). Suppressing dust grains in the first model also addresses uncertainties introduced by Cloudy’s inaccurate treatment of dust sublimation at small radii where temperatures are high enough for dust to be destroyed.

In order to accommodate the different environmental parameters, the simulations is split into two separate runs. Run 1 extends from the inner radius $r_{in} = 10^{13}\text{cm}$ (about 0.7 AU) to an outer radius $r_{out} = 3 \times 10^{17}\text{cm}$. The outer boundary was picked deliberately to be around 0.1pc, the right order of magnitude for the nebula seen in Mirabel et al. (1996a). As we defined an external boundary to the simulation in form of a radius, no additional stopping criterion is needed for run 1.

For the second part of the simulation, we assume the same physical conditions as seen in the last simulated zone of run 1, and let the simulation run freely from there assuming hydrostatic equilibrium, not forcing a constant density. Obviously, the inner radius of this simulation corresponds to the outer radius of run 1, i.e. $r_{in,2} = r_{out,1} = 3 \times 10^{17}\text{cm} \approx 0.1\text{pc}$. At the start of the simulation, the hydrogen number density and the temperature are forced to the respective values of the last zone in run 1, which can be found in the
Table 3: Final set of parameters for the two-step model for Cygnus X-1.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Run 1</th>
<th>Run 2</th>
</tr>
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<td>39.6451477</td>
<td>39.6451477</td>
</tr>
<tr>
<td>density law</td>
<td>(n_H) constant (-1.0)</td>
<td>hydrostatic equilibrium, (P_{tot} = \text{const})</td>
</tr>
<tr>
<td>log(hydrogen density) [cm(^{-3})]</td>
<td>solar, no dust</td>
<td>ISM, dust grain chemistry included</td>
</tr>
<tr>
<td>at inner face: Abundances</td>
<td></td>
<td>0.003</td>
</tr>
<tr>
<td>dust depletion</td>
<td></td>
<td>167840 K</td>
</tr>
<tr>
<td>temperature at inner face of the nebula</td>
<td></td>
<td>15849 dyne cm(^{-2})</td>
</tr>
<tr>
<td>pressure at the inner face of the nebula</td>
<td></td>
<td>3 \times 10^{17} to 10^{19}</td>
</tr>
<tr>
<td>inner/outer radius [cm]</td>
<td>10^{13} to 3 \times 10^{17}</td>
<td>outer radius set</td>
</tr>
<tr>
<td>stopping criterion</td>
<td>outer radius set</td>
<td>outer radius set</td>
</tr>
</tbody>
</table>

output file of punch physical conditions in the second and fourth columns. The initial temperature in a simulation can be set using the force temperature command, and the initial density is specified via hden. Unfortunately, the punch-commands do not output the pressure in each zone. Therefore, the pressure is found iteratively in order to match up with that of the previous zone. If the pressure has a value that is too high or too low, at least one of either density and temperature will jump in the first zone from the value it was forced to in the input script to that value that fits hydrostatic equilibrium with that particular pressure. By adapting the pressure in each run until both temperature and density in the first zone of run 2 match the corresponding values in the last zone of run one, I find the appropriate pressure. Both simulations use an ISM abundance pattern is assumed, yet this time including a small dust grain component. The parameters used are summarized in Table 3.

Figure 21 shows the final spectrum for Cygnus X-1 in the two-model approach. The output spectrum is quite similar to that in the constant-density approach, shown in Figure 18. The free-free emission in the radio and far-infrared is a bit less prominent, due to the small number density in the inner region. The dust blackbody has about the same temperature in either models, and again ionization lines of higher-order ionized elements are visible. In the UV, the spectrum is mostly optically thin, with small absorption features. In general, this model seems to do no better or worse than the constant-density model. While it is likely that the environment around Cygnus X-1 is rather complex, the predictions for line emission doesn’t seem to vary much between simple and more involved models, unless the environment itself is vastly different from what is presented here. All in all, only little radiation is reprocessed in the region around the source itself. Most likely, the largest fraction of UV radiation is actually absorbed in the interstellar medium between us and the source, not in the ionized region directly around it. This makes it hard to make any meaningful predictions about the source physics itself from the observations modified by the ionized nebula around it.
Figure 21: Final spectrum for the two-model run for Cygnus X-1.
6.6 Other Ways of Approaching the Model

So far, we have not really taken into account the presence of the stellar wind. This wind has a rather complicated geometry due to the black hole primary’s strong gravitational attraction and is proposed to be highly focussed (Friend & Castor, 1982) and therefore anisotropic. It can be measured to have a number density around $2.2 \times 10^4 \text{ cm}^{-3}$ and a terminal velocity of $\approx 2100 \text{ km s}^{-1}$ (Hanke et al., 2009). In theory, Cloudy has the capabilities to model a stellar wind with either a spherical or disc geometry using the \texttt{wind}-command. This type of modelling has been attempted with Cloudy before for the X-ray binary Cygnus X-3. Szostek & Zdziarski (2008) use X-ray spectra taken with BeppoSAX and model the stellar wind using Cloudy. They find that a two-phase model is needed to model X-ray line profiles in the stellar wind accurately. I would propose that a model of this type could be the basis for a more complex modelling approach of Cygnus X-1, taking into account effects of the different emission regions as well as different phases in the interstellar medium, including the stellar wind, into account. Detailed X-ray spectroscopy of Cygnus X-1’s wind and subsequent modeling has been performed by Hanke et al. (2009) and Hanke et al. (2010) and could present the foundation for broadband modeling with Cloudy. In this approach, Cygnus X-1 would have to be simulated using a succession of models that all describe the different media between us and the source that Cygnus X-1 has ionized. Since these media will manifest in the spectrum in different parts of the spectrum, the constraints we have from observations may be effective at constraining the individual models, working towards a more realistic simulation of the system as a whole. This kind of simulation, in turn, may be much more reliable at making predictions for observations, as well as drawing conclusions about individual emission mechanisms.

7 Modelling GX 339-4

While Cygnus X-1 is perfectly suited to test our models, the bright companion renders it less useful when trying to constrain the UV flux in order to make predictions about jet models. Hence, an LMXB is a more natural choice for this type of analysis. GX 339-4 was chosen for its relatively large body of multi-wavelength data. Additionally, its frequent, well-studied outbursts make it relatively well understood. Modelling GX 339-4 is in some ways easier than Cygnus X-1, because it shows a much tighter correlation between radio and X-ray flux (Corbel et al., 2003a; Xue & Cui, 2007), setting a very tight constraint on the upper limit of nebular free-free emission. There is little known about the environment of the source, but the fact that it is an LMXB implies that it is likely to be old and has probably travelled far from its birthplace. Therefore, it is reasonable to assume it to be in an ISM-line environment.

The input spectrum (in Figure 22) for the Cloudy simulations was taken from Markoff et al. (2005), Figure 1. This spectrum was chosen because is based on quasi-simultaneous observations of GX339-4 in the low, hard state, where a jet is present. The particular model chosen from Markoff et al. (2005) is a representative simulation that illustrates the relative contributions from several radiative components to the spectrum. For this
Figure 22: Observed and model broadband spectrum for GX 339-4 used for all subsequent Cloudy models of this source. Taken from Markoff et al. (2005), Figure 1

preliminary analysis, where the general question whether there is a bump in the UV part of the spectrum or not is examined, this is sufficiently accurate. The spectrum was extracted using Engauge Digitizer 4.1, a software specialized in extracting information from plots. The total luminosity of the spectrum was subsequently calculated using the same method as detailed for Cygnus X-1, using the script in Appendix B. To be consistent with (Markoff et al., 2005), I used the distance estimate given by Hynes et al. (2004) for the source’s distance $d = 6\text{kpc}$, and consequently find $4\pi d^2 = 4.30739011 \times 10^{45}\text{cm}^2$. The average luminosity, using these values, is $L_{\text{GX339}} = 5.76423432583 \times 10^{37}\text{erg s}$, log $L_{\text{GX339}} = 37.7607416273$.

7.1 Environment Parameters

The environmental parameters for GX 339-4 are much more speculative than for Cygnus X-1, and thus I chose rather generic values. Since GX 339-4 is an LMXB, it is likely to be old, and hence unlikely to be within its supernova remnant. Additionally, the companion has not been detected so far, but conservative estimates place it as an evolved K-star. Thus, there are no stellar winds or other dynamics process that would greatly complicate the dynamics of the system. As for Cygnus X-1, I start with the simplest approach, a constant-density model, and simply assume typical ISM densities for the surrounding medium in the absence of better constraints. Unlike Cygnus X-1, there is
no bright component from the companion that would dominate the optical/UV spectrum. Additionally, the radio-X-ray correlations in GX 339-4’s hard state are much tighter than for Cygnus X-1 (Corbel et al., 2003b), indicating that the radio spectrum is completely dominated by the jet, which leaves no room for a possible significant contribution by interstellar free-free emission. Since there are - to my knowledge - no far-infrared/submillimetre observations of GX 339-4, it is impossible to say whether there is a significant dust contribution in the spectrum, thus I included a small dust contribution in the final model to account for possible dust in the system. The dust contribution is larger than for Cygnus X-1, as there is no stellar wind which could destroy dust, but smaller than typical for the ISM, because the strong radiation field will sublimate dust at least at radii close to the binary.

Following the assumptions above, I ran several models with column density as stopping parameter (Figure 23). Dust was left out of this preliminary simulation in order to see the effect of free-free emission with stopping radius more clearly and to reduce the runtime of the code. As already seen in Section 6.2.3, the infrared to radio continuum increases strongly with stopping radius, owing to the fact that the further out the stopping radius is, the more material the radiation can pass through until the simulation ends, and consequently more radiation is reprocessed to smaller wavelengths. Since we assume that

Figure 23: Testing different stopping column densities for GX 339-4.
free-free emission can only be a very small part of the millimeter and radio spectrum, we chose an upper limit of $r_{outer} \approx 2 \times 10^{19}$ cm $\approx 6$ pc for the outer radius. This is of the same order as some HII regions observed in our galaxy. I thus choose a model with parameters specified in Table 4 as the best possible model.

Table 4: Final set of parameters for the best model for GX 339-4.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>log(Luminosity) [erg s$^{-1}$]</td>
<td>37.7607416273</td>
</tr>
<tr>
<td>density law</td>
<td>constant density</td>
</tr>
<tr>
<td>hydrogen density</td>
<td>1.0 cm$^{-3}$</td>
</tr>
<tr>
<td>Abundances</td>
<td>ISM, grain chemistry included</td>
</tr>
<tr>
<td>grain abundances</td>
<td>0.1 typical ISM grain abundances</td>
</tr>
<tr>
<td>inner/outer radius [cm]</td>
<td>$10^{12}$</td>
</tr>
<tr>
<td>stopping criterion</td>
<td>column density $N_H = 2 \times 10^{19}$ cm$^{-2}$</td>
</tr>
</tbody>
</table>

7.2 Results

Figure 24 presents the best-model spectrum for GX 339-4. The model spectrum is very different from that presented for Cygnus X-1. The dust black body is much more pronounced, which owes to the lower dust depletion in this model compared to the simulations run for Cygnus X-1. Dust is much more likely to exist in GX 339-4 than in Cygnus X-1, as there is no stellar wind blowing out a bubble whose energetic shock wave is very efficient at destroying dust. Additionally, we assume the environment of GX 339-4 to be ISM-like, if the source is old and has travelled far from its birthplace (as seen in e.g. XTE J1118+480, see Mirabel et al., 2001). The dust depletion incorporated owes to the nevertheless harsh X-ray flux that is likely to cause the destruction at least some dust at small radii via sublimation. The blackbody produced by dust grains in this model peaks at about $3 \times 10^{12}$ Hz, corresponding to $\lambda = 78.457 \mu$m and a black body temperature of $T_{bb} \approx 37$ K. Another dominating feature is the presence of several ionization lines in the infrared spectrum. In the far-infrared, there are nebular emission lines that may belong to two [NeV] transitions at $\lambda 24.3 \mu$m and $\lambda 14.3 \mu$m, the ratio of which is an important diagnostic of the electron number density. Additionally, the spectrum shows recombination lines of $He^+$ at $\lambda = 6560$ Å and 4680 Å. In the optical and UV, some absorption as well as emission features are visible. The Lyman-\(\alpha\) hydrogen transition is visible as absorption feature at $\lambda = 1216$ Å, as well as another HI recombination line at $\lambda = 1026$ Å. If these predictions are correct, then they may present valuable constraints for future observations, especially when it comes to interpreting the presence of single-peaked emission lines sometimes observed in the spectra.
Figure 24: The best model spectrum for GX 339-4 following the parameters in Table 4
In recent years, a growing fraction of research has been devoted to the early universe, in particular how the first stars and subsequently galaxies formed and evolved. There is a long timespan between the surface of last scattering at a redshift of \( \approx 1000 \) (Bennett et al., 2003), from which the cosmic microwave background (CMB) is observed, to the detection of high-redshift quasars at \( z \approx 6 \) (Fan et al., 2003). For this period, the first part of which is often called the “dark ages” as there were no radiation-emitting sources yet, we have virtually no observational information. We know that somewhere in these first few tens of millions of years, the first stars formed, reionizing the surrounding material with their large flux of UV photons, and subsequently massive galaxies evolved from the first proto-galactic haloes as well (Barkana & Loeb, 2001). How exactly this happens is a matter of debate and intense computational modelling, yet knowledge of these early phases are crucial in the context of galaxy formation and evolution. Observational constraints are sparse: although the 21-cm hyperfine hydrogen line was suggested as a probe of this early epoch decades ago (Sunyaev & Zeldovich, 1975), the technical difficulties have made the construction of appropriate radio instruments feasible only in the last decade or so. With the advent of new large-scale instruments like LOFAR and MWA, it will soon be possible to detect the signal from these early times, often called
Epoch of Reionization (EoR), and thus test model predictions (e.g. Bowman et al., 2006; Harker et al., 2010). Much computational work has focussed on how the first sources ionize the intergalactic medium (for an example see e.g. McQuinn et al., 2007). An example of a simulation of how the inter-galactic medium (IGM) was ionized during the EoR is shown in Figure 25: the first stars carve out ionized bubbles (in white) in the neutral IGM (in black). As more stars and subsequently the first proto-galaxies form, these bubbles grow, emitting large numbers of ionizing photons until the whole IGM is ionized.

These simulations suffer somewhat from uncertainties in the distribution of ionizing sources. It is believed that the largest fraction of ionizing photons originates in the very first, metal-free (population III) stars that formed from the primordial gas (Venkatesan et al., 2003). These stars are believed to be very massive, often with $M_\star > 100 M_\odot$ (Bromm et al., 1999; Bromm, 2000), and to explode as pair-instability supernova (Heger & Woosley, 2002). This type of supernova does not leave a compact remnant behind, but disrupts completely, enriching the environment in both energy and metals. However, stars with masses $40 M_\odot \lesssim M_\star \lesssim 150 M_\odot$ and $M_\star \gtrsim 250 M_\odot$ may have collapsed to black holes with masses comparable to those of their progenitors (Fryer et al., 2001). These intermediate-mass black holes, sometimes called mini-quasars, may have provided the seed population for the evolution into supermassive black holes now found at the centres of active galaxies (Kuhlen & Madau, 2005), yet their role in reionization itself is unclear.

Quasars, massive active galaxies, are more effective than stars in ionizing the intergalactic hydrogen, because of their hard emission spectrum, the higher efficiency of accretion flows as compared to stellar radiative efficiencies, and their higher luminosities (Barkana & Loeb, 2001). It has thus been proposed that mini-quasars, as they formed from the first population of stars and grew towards becoming supermassive black holes, may have played a crucial role in the first stages of reionization (Kuhlen & Madau, 2005; Thomas & Zaroubi, 2008). We do not have any modern-day equivalents to these proposed first, massive black holes, except for a potential connection to ULXs, should these sources be intermediate-mass black holes after all (e.g. Patruno et al., 2006). However, using a similar argument as for the connection between AGN and microquasars, we may be able to make inferences about the properties of these mini-quasars via mass scaling. Therefore estimating the effect of a microquasar as we see it today on the kind of environment that would have existed in the early universe should lead to valuable insights about the importance of black-hole systems during this epoch.

In order to estimate the effect of a microquasar on the medium as it may have existed in the early universe during the EoR, I ran a simple model, using the two sources utilized for the analysis above. Unlike the previous models for Cygnus X-1 and GX 339-4, this model is far simpler, with a constant-density law, involves no grain chemistry and uses the primordial abundance set stored in Cloudy. The model parameters are given in Table 5. I modeled both source, yet Cygnus X-1 with its high-mass O-star companion is probably the closer analogue to the type of microquasar object that may have existed during the EoR. The existence of an object like GX 339-4 with its low-mass, evolved companion is much more unlikely, and the model of this source is included mainly to illustrate the effect that a black hole system itself - without interference from a bright
companion - may have had on its surroundings during the EoR. This type of system could be realized if a black hole is not fed by a companion, but accretes matter from an accretion disc formed from stellar material after the supernova explosion.

Table 5: Model Parameters for the EoR model run for Cygnus X-1 and GX 339-4.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Cygnus X-1</th>
<th>GX 339-4</th>
</tr>
</thead>
<tbody>
<tr>
<td>log(Luminosity) [erg s^{-1}]</td>
<td>39.6451477</td>
<td>37.7607416273</td>
</tr>
<tr>
<td>density law</td>
<td>constant density</td>
<td>constant density</td>
</tr>
<tr>
<td>hydrogen density [cm^{-3}]</td>
<td>1.0</td>
<td>1.0</td>
</tr>
<tr>
<td>Abundances</td>
<td>primordial</td>
<td>primordial</td>
</tr>
<tr>
<td>inner radius [cm]</td>
<td>10^{13}</td>
<td>10^{13}</td>
</tr>
<tr>
<td>stopping criterion</td>
<td>temperature 4000 K</td>
<td>temperature 4000 K</td>
</tr>
</tbody>
</table>

Figure 26: EoR simulations for (a) Cygnus X-1 and (b) GX 339-4. Simulations extend to the maximum ionization radius, i.e. the radius where the electron temperature falls below 4000 K.

Figure 26 shows the results of the two model runs for (a) Cygnus X-1 and (b) GX 339-4. The spectrum from optical to radio is dominated by free-free, free-bound and line emission from nebular material around the source. In the optical, very strong hydrogen lines are visible. As expected, the UV-band is highly absorbed due to the large amount of reprocessing. The free-free emission is about an order of magnitude stronger for Cygnus X-1 than GX 339-4. This is expected, as Cygnus X-1’s companion dominates the UV emission strongly.

If the source is radiation-bounded, then the resulting HII region will be very large: of the order of hundreds of parsecs for the constant density model above. Within this structure, at least a fraction if the material is ionized by radiation from the jet as well as as the companion star in the case of Cygnus X-1. The main ionizing sources for GX
339-4, where the companion star is not visible, are the jet and the accretion disc.

Table 6: Luminosities for different wavebands, and for the input spectra as well as the spectra at the far side of the cloud. All luminosities in units of $10^{38}$.

<table>
<thead>
<tr>
<th>Luminosity [erg s$^{-1}$]</th>
<th>Cygnus X-1</th>
<th>GX 339-4</th>
</tr>
</thead>
<tbody>
<tr>
<td>$L_{\text{UV, input}}$</td>
<td>3.2</td>
<td>0.217</td>
</tr>
<tr>
<td>$L_{\text{UV, output}}$</td>
<td>5.4</td>
<td>0.557</td>
</tr>
<tr>
<td>$\Delta L_{\text{UV}}$</td>
<td>2.66</td>
<td>0.16</td>
</tr>
<tr>
<td>$L_{\text{IR, input}}$</td>
<td>6.68</td>
<td>0.02</td>
</tr>
<tr>
<td>$L_{\text{IR, output}}$</td>
<td>8.99</td>
<td>0.17</td>
</tr>
<tr>
<td>$\Delta L_{\text{IR}}$</td>
<td>2.31</td>
<td>0.15</td>
</tr>
<tr>
<td>$\Delta L$</td>
<td>0.35</td>
<td>0.01</td>
</tr>
</tbody>
</table>

Using this very basic simulation, I can do some energetics. With the help of the script given in Appendix B, I can calculate luminosities in different parts of the spectrum in both input and output spectra of the two sources and compare them. I take frequency bounds of $\nu_{l,\text{UV}} = 3 \times 10^{15}$ Hz to $\nu_{u,\text{UV}} = 2 \times 10^{17}$ Hz for the UV waveband, where radiation is absorbed and reprocessed, and $\nu_{l,\text{IR}} = 3 \times 10^{8}$ Hz to $\nu_{u,\text{IR}} = 3 \times 10^{15}$ Hz as bounds for the part of the spectrum where emission from the environment is visible. For Cygnus X-1, the UV luminosity absorbed in the interstellar medium amounts to about $2.6 \times 10^{38}$ erg s$^{-1}$, i.e. almost a tenth of the total luminosity. The largest fraction of this emission is reprocessed into emission lines and continuum emission ranging from optical to radio wavelengths. However, a small part, about $10^{-2}$, of the original energy is being used to heat the gas and remains as heat. The situation is similar for GX339-4, albeit less pronounced due to the smaller UV luminosity of the source. The reprocessed luminosities, as well as the amount of energy lost in heating the ISM are a bit more than an order of magnitude smaller than for Cygnus X-1, in agreement with the fact that the total luminosity is more than an order of magnitude smaller. Nevertheless, with Strömgren radii of 360 pc for Cygnus X-1 and 84 pc for GX 339-4, it is clear that microquasars are able to put a considerable amount of energy into the medium over large distances.

In Figure 27, I show the ionization structure for the EoR model for Cygnus X-1. The innermost region is dominated by the intense radiation field that ionizes helium to HeIII. Only when most electrons $h\nu > 54.4$ eV are used up does the nebula show HeII. The far-UV and X-ray radiation field is strong enough that the outer boundaries of the HII region and HeII regions coincide. Hence, out to a radius of at least $5 \times 10^{20}$ cm $\approx 160$ pc around the source, both helium and hydrogen will be completely ionized.
Figure 27: Ionization structure for the HII region around Cygnus X-1 for the Epoch of Reionization model run.
9 Discussion

In the work above, I have shown that it is possible, but not straightforward, to model the medium around an XRB using a photoionization code. Cygnus X-1 presented itself as a natural source to calibrate our models: since its UV spectrum is strongly dominated by the main-sequence companion, the UV flux is effectively known due to the simple and well-known shape of stellar black bodies. Although the observations were not performed simultaneously, a good understanding of the Cygnus X-1 hard state makes it possible to synthesize a detailed broad-band spectrum that was used for modelling in Cloudy. By exploring the model’s parameter space, it was possible to narrow down the large number of possible parameters to very few that the model is very sensitive to. Only one quantity crucially determines the overall shape of the spectrum: the amount of material the radiation passes through, set by a combination of initial hydrogen density, density law and stopping parameters. If the total column density the radiation passes through until the simulation is stopped remains similar, then the exact shape of the density law is relatively unimportant. I can therefore conclude that as long as there is a good constraint on the column density of material ionized by the source, the exact density structure of the surrounding medium is not significant. The other parameter that has an appreciable effect on the resulting spectrum is the amount of dust in the system. Depending on the dust-to-gas ratio, the far-infrared/sub-millimetre spectrum shows thermal emission of varying strengths from dust grains heated by radiation from the XRB. Here, observational constraints from infrared observations are crucial and could help to constrain the dust contribution to the spectrum. Previous infrared observations indicate that here is likely to be warm dust in Cygnus X-1, and dust emission has previously been observed in GRS 1915+105 (Mirabel et al., 1996b). The state of the dust in the system can tell us a lot about the dynamics and structure of the ionized region around the source, and those will give important clues about the central source itself.

9.1 Modelling Microquasars in Cloudy

Our best constraint on the model comes from the fact that in many X-ray binaries, radio and X-ray fluxes are tightly correlated, as is the case for GX 339-4 (Corbel et al., 2003a). This is a clear signature of synchrotron emission from the jet dominating the radio, and excludes any appreciable contribution to that part of the spectrum from free-free emission in the surrounding material. If we can estimate the hydrogen density in the medium, then an upper limit to the hydrogen column density - if it is used as a stopping parameter - can be found by not allowing a free-free emission contribution to the radio spectrum. The case is less clear for Cygnus X-1: the correlation between radio and X-ray flux does show a certain degree of scatter, which has largely been attributed to a contribution from the stellar wind (Gleissner et al., 2004). However, the models above show a clear trend that the interstellar medium could possibly be responsible for at least a part of the scatter. By incorporating the stellar wind into the Cloudy model, this idea will be explored further in the near future. The temperature structure of Cygnus
X-1 for a model where the column density is constrained shows that the ionized nebula is matter-bounded, e.g. by a change of ISM density, as opposed to radiation-bounded, where the outer radius of the nebula coincides with the ionization front at which all ionizing radiation has been absorbed by the nebula. The spectra for both Cygnus X-1 and GX 339-4, when the model is constrained in that way, show that the nebula is largely optically thin to UV radiation. From this, I conclude that the largest fraction of UV flux is absorbed in the interstellar medium between us and the source, and not in the ionized nebula directly surrounding the XRB. This makes it difficult to directly estimate the UV flux from the radiation that is reprocessed into infrared. However, the model spectra do show strong line emission in the infrared part of the spectrum, and small absorption features in the UV. The nebular emission lines present the most promising approach to constraining both the nature of the nebula as well as the flux from the source. If we can measure the strengths of these nebular emission lines from observations, then we should be able to associate these nebular emission lines to the absorption features seen in the model, and consequently estimate the UV flux at least for a few frequencies. With the data published to date for Cygnus X-1 and GX 339-4, this is not yet possible. However, Heinz et al. (private communication) have observed Cygnus X-1 with the IRS spectrograph on board the Spitzer Space Telescope. The analysis of possible nebular emission lines and comparison to the models above is one of the next steps to be performed, and should give us the necessary constraints to constrain the UV flux.

While Cygnus X-1 is a valuable source for calibrating the model and a perfect test-bed, it is only of very little use when trying to distinguish between jet models via constraining the UV flux due to its bright companion. For this reason, GX 339-4 was incorporated into the work above, in the form of a broadband spectrum defined by radio and X-ray observation as well as the jet model presented in Markoff et al. (2005). Although its luminosity is considerably lower, nebular line emission predicted in the infrared band is appreciable and should be detectable with modern infrared spectrographs on large telescopes. With new high-resolution instruments at long wavelengths already in place (e.g. Spitzer, Herschel) or becoming available in the next years (e.g. ALMA), highly resolved spectral studies of the environment around X-ray binaries may be feasible.

There are emission lines visible in the optical part of the spectrum as well, albeit much less pronounced, owing to the fact that GX 339-4 has no companion which dominates that part of the spectrum. These lines could explain the single-peaked emission features sometimes observed in optical spectra which are hard to reconcile with the idea that the emission lines originate in the accretion disc: in the latter case, the lines should be double-peaked, something that has been observed as well. The question to be answered in the case of single-peaked lines is whether the peaks are simply too small to be resolved with current spectrographs, or whether they may indeed originate in the surrounding medium rather than the XRB itself. The ionization structure for Cygnus X-1’s circumstellar environment shows an inner region of doubly ionized helium out to $10^{20}$ cm, created by the strong X-ray emission above 54.4 eV. This structure is likely to be too diffuse to be imaged directly and the companion is too bright for optical emission lines to be seen in the spectrum, but this is not the case in GX 339-4. Indeed, HeII
emission is seen in the model spectrum and should be detected in optical spectra.

9.2 Beyond Cygnus X-1 and GX 339-4

The rather different models used above to model Cygnus X-1 and GX 339-4 make it clear that there is no universal recipe for modelling X-ray binaries yet. However, the fact that it is possible to create a model of the environment around an X-ray binary that depends on relatively few crucial parameters is encouraging for future prospects of parametrizing the approach. As more X-ray binaries are modeled in this way, our understanding of the model and its response to a given set of input spectra and parameters will deepen, and future work will include developing a generalization valid for most X-ray binaries for which broadband data exists. This more general model will be dependent on only a few parameters: the source’s type (high-mass vs. low-mass X-ray binary), the intrinsic luminosity and constraints about the environment known by other means. In general, it should be possible to model LMXBs like GX 339-4 with relatively similar models, because they tend to be old and far from their place of birth (Mirabel et al., 2001). Consequently, the environment is likely to be ISM-like with typical ISM hydrogen densities and abundances. In this case, a constant-density model is a good approximation. If we then assume these sources to have an intrinsically similar shape, the only free parameters in the Cloudy model are the distance and the source luminosity. Similarly, while high-mass X-ray binaries are likely to be located in rather complex environments, the nature of the environment should not change drastically with source. They are likely to have some form of stellar wind, probably a wind-blown bubble, and are usually located close to their birthplaces in star-forming regions. The two models for Cygnus X-1 presented above are a good starting point for simulating HMXBs; if we can incorporate the effects of the stellar wind as well, then we have a reasonably good model to make predictions from.

9.3 Modelling the Epoch of Reionization

Cloudy’s capability to simulate nebulae with primordial element abundances makes it very easy to run simulations for the EoR. The models above show that for a HMXB like Cygnus X-1, about a tenth of the source’s total luminosity is reprocessed in the interstellar medium, assuming a radiation-bounded nebula. During reprocessing, a fraction of approximately $10^{-2}$ of the total luminosity is not emitted again via line or continuum emission, but lost in heating the gas to very high temperatures. For a source like Cygnus X-1, this is still of the order of $10^{37}$ erg s$^{-1}$. The HII regions created this way can be greater than 100 pc in radius, and their inner regions, of the order of several tens of parsecs, are completely ionized up to HeIII. This ionization of helium has its origin in the strong X-ray emission and can hardly be achieved with normal stellar blackbodies. GX 339-4 has a luminosity more than an order of magnitude lower than Cygnus X-1, and no strong companion dominating the UV spectrum, therefore it emits fewer ionizing
photons, resulting in a smaller ionized nebula and less radiation reprocessed to longer wavelengths. The model results are consistently smaller for GX 339-4 than for Cygnus X-1, by slightly more than an order of magnitude, in concordance with the diminished source luminosity. However, the presence of LMXBs in the early universe is in itself very unlikely: as presented above, the first stars are likely to have been very massive and metal-free, rather unlike the more evolved, low-mass stars found in LMXBs. However, if the first black holes were not located in binary systems, but accreted matter from surrounding discs created by their own supernova, then scaling up GX 339-4’s to a mini-quasar should give more valuable insight. For binary star systems in the early universe, however, microquasars of the type of Cygnus X-1 present a better blueprint for modelling. For either case I have shown that the energy input into the environment is substantial and that micro- and miniquasars should be taken into account when modelling the early Epoch of Reionization.

9.4 Future Prospects

The work presented above is only a starting point and initial exploration of Cloudy’s capabilities and limitations in modelling X-ray binaries. There is much to be explored along this line of research that is beyond the scope of the current work. Incorporating a stellar-wind model will be crucial for the correct treatment of HMXBs like Cygnus X-1, and should significantly contribute towards explaining the scatter in the radio/X-ray correlations for these sources. Cygnus X-1’s stellar wind has been extensively monitored and modeled in X-rays (Hanke et al., 2009, 2010). The results from these studies can provide a starting point for a broader treatment in Cloudy in order to disentangle the influence of stellar wind and environment on the low-energy part of the spectrum.

Furthermore, the fact that XRB systems are highly variable systems has not been addressed, and all solutions above are calculated as having relaxed into thermodynamical equilibrium. For XRB systems this need not be true, since they vary on small time scales: weeks to months. Thus, exploring the time-dependent evolution of the structure may be worthwhile. Here, line emission may especially be of interest. It could interesting to see how nebular emission lines respond to an X-ray binary outburst, when the UV emission from the accretion disc is much stronger than during the low-hard state. As the photoionized region could be of the order of parsecs, these changes may be observed over months to years. How the emission lines, particularly He$^+$ and H$^+$ recombination lines, change, should give us important hints about the density structure of the medium around the XRB. In GX 339-4, for example, an outburst may cause stronger emission lines, which will be visible long after the source itself has gone back to the LHS. Thus, observations in the LHS in the months after an outburst may present the best opportunity to find nebular emission lines in the spectrum: as the increased UV flux from the outburst makes its way through the ISM, it strengthens the emission lines. At the same time, the continuum flux due to the jet and accretion disc is low, such that the increase in prominence of emission lines may make them visible.
Another promising line of research may come from extragalactic sources, for example extragalactic microquasars and ultraluminous X-ray sources (ULXs). In these sources, it is possible to circumvent the problem of low surface brightness due to largely diffuse emission that makes it so difficult to detect nebulae around X-ray binaries in our own galaxies. Extragalactic microquasars like LMC X-1 and ULXs like NGC5408 X-1 are both far away enough and bright enough to excite X-ray ionized nebulae bright in HeII $\lambda 4686\text{Å}$ emission (e.g. Pakull & Mirioni, 2003; Kaaret et al., 2004). In fact, modelling attempts using Cloudy for these sources are somewhat more advanced, since they are often undetected in most wavebands except X-rays and thus their photoionized nebulae are often the only way to gain insights into the intrinsic properties of these sources (Berghea et al., 2010).

At the same time, the theoretical treatment of the interaction between X-ray binaries and their surrounding medium is far from complete. The results above are based on very simple models that may or may not accurately represent the physical environment. In particular, the medium around the two chosen X-ray binaries may be non-uniform, as indicated by the presence of a jet-blown nebula in Cygnus X-1 (Gallo et al., 2005; Russell et al., 2007). This has not been addressed above, since Cloudy performs one-dimensional simulations, but there are extensions to Cloudy that make a pseudo 3-D treatment possible (see e.g. Morisset, 2006). Cloudy itself also has the capabilities to simulate some dynamical time evolution of changes in the source or the medium. In the currently released version, they are only available as a preliminary implementation, and the user is cautioned not to treat results as absolutely correct. It remains to be seen how dynamical simulations will be treated in the new Cloudy C10.0 when it is released. If it was indeed possible to model the response of the nebular spectrum to outbursts, this might give further constraints to observations of both emission lines and the continuum.

10 Conclusion

In this thesis I have shown that on the basis of model calculations performed with a sophisticated photoionization code, X-ray binaries interact strongly with their environment, and that the environment can have strong effects on the spectrum, attenuating emission and producing emission lines. Cygnus X-1 is well-suited as testbed for our models, thanks to a good broadband coverage in archival data and the companion’s domination in the UV effectively enabling us to infer the UV flux from the stellar blackbody spectrum. Low-mass X-ray binaries like GX 339-4 are more useful for our goal of discerning between different jet and corona models. I find that the models are strongly dependent on the column density of material the radiation passes through, defined by the combination of hydrogen number density, density law and stopping parameter. However, if the total column density remains constant, the models only weakly depend on the density law used. On the basis of this observation, I conclude that low-mass X-ray
binaries like GX 339-4 can be modeled with a relatively simple environment and should be easy to parametrize, while the stellar wind in HMXBs may call for a more complicated solution. Nevertheless, it should be possible to introduce a parametrization for our Cloudy models, allowing to model various other black hole sources by defining only a few key parameters. Together with the stellar-wind treatment for Cygnus X-1, this is a key task for the future.

A strong constraint for the total column density comes from the tight correlations between radio and X-ray flux observed in many X-ray binaries. As this correlation implies the radio cannot be dominated by environmental free-free emission, this sets an upper limit on the amount of material the radiation passes through in the model, and at the same time implies that ionized nebulae around X-ray binaries are rarely radiation-bounded, but rather matter-bounded. The spectra for a nebula constrained in this way show that the HII region is largely optically thin to UV radiation, implying that most of the UV radiation is reprocessed in the interstellar medium between the source and Earth, and not in the photoionized region directly surrounding it. I report the presence of strong nebular emission lines in the far-infrared spectrum, notably from [NeV], and somewhat less pronounced optical emission lines of helium. The latter are a hallmark sign of material subjected to strong X-ray radiation above 54.4 eV. The presence of far-infrared lines, as well as a pronounced dust blackbody spectrum in the same wavelength range, call for spectroscopy with high-resolution instruments like Spitzer, Herschel and in the near future ALMA. Spitzer spectroscopy and photometry has been performed for Cygnus X-1 by Heinz et al. and is due to be analyzed in the near future. For GX 339-4, no far-infrared spectroscopy has been performed. Since these lines are a major prediction of our models, and our best bet for constraining the UV flux, observations of the source at these wavelengths are deemed very beneficial.

Finally, modelling the environment around X-ray binaries may have important implications for large-scale dynamical simulations of the early universe, particularly the Epoch of Reionization. I have shown above that in principle, the power input into the ISM from an X-ray binary is considerable, and that a source of this type is able to inflate ionized regions of several hundred parsecs around it. Thus, their presence may have been important in the early universe, and this is a line of research that should be explored in the future.
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Appendix A: Sample Cloudy Script

As an example, below is the script for the constant-density model used in Section 6.4.

abundances ism no grains \ use ISM abundances without grains
gains ism 0.001 \ add ISM-like dust grains at a 0.001 fraction
no induced processes (OK) \ ignore induced processes (increases simulation speed)
distance 2000 linear parsecs \^A set the distance to the source
c Output Commands \ make files with spectrum, ionization structure, temperature etc.
punch continuum units MHz file="cygx1_consthden_small.cont"
punch transmitted continuum last file="step1.trans" \ cont. for use in Cloudy models
punch physical conditions file="cygx1_consthden_small.phys"
punch overview file="cygx1_consthden_small.ovr"
punch radius outer "cygx1_consthden_small_radius.outer"
c Continuum commands
interpolate (8.55604 1.2839) \ the following lines are the spectrum in pairs of
continue (9.39006 1.16525) \ energy (Rydberg) and flux (mJy)
continue (9.95446 1.18009)
continue (10.2341 1.04661)
continue (11.2429 0.898305)
continue (11.4128 1.0911)
continue (13.4262 1.87712)
continue (13.7913 2.48517)
continue (14.2814 3.36017)
continue (14.4064 3.58263)
continue (14.5415 3.89407)
continue (14.9214 4.35381)
continue (14.9865 4.53178)
continue (15.1314 4.72458)
continue (15.2956 4.97669)
continue (15.4262 4.7839)
continue (15.5508 4.50212)
continue (16.7018 0.586864)
continue (16.7618 0.705509)
continue (16.8568 0.75)
continue (16.9167 0.824153)
continue (17.0067 0.868644)
continue (17.0766 0.898305)
continue (17.1615 0.898305)
continue (17.2364 0.853814)
continue (17.3363 0.76483)
continue (17.436 0.616526)
continue (17.5258 0.45339)
continue (17.6006 0.260594)
continue (17.6505 0.112287)
continue (17.7302 -0.0805082)
continue (17.8101 -0.169492)
continue (17.9249 -0.273305)
continue (18.0946 -0.406779)
continue (18.6189 -0.67373)
continue (18.9933 -0.866525)
continue (19.3079 -1.02966)
continue (19.5575 -1.20763)
continue (19.7122 -1.40042)
continue (19.8319 -1.54873)
continue (19.9267 -1.71186)
continue (20.0464 -1.91949)
continue (20.2011 -2.2161)
continue (20.3456 -2.6017)
continue (20.4503 -2.88348)
continue (20.5849 -3.32839)
continue (20.7344 -3.68432)
continue (20.9091 -3.89195)
continue (21.2283 -4.60381)
continue (21.947 -5.34534)
luminosity 39.6451477441  \ total luminosity of the source
hden 1.0 linear \ hydrogen number density
constant density \ density law: constant density
radius 13.0 17.8 \ inner and outer radius of the cloud
c stop temperature 4000K  \ stopping parameter: lower temperature limit (commented out)
c stop column density 19.5  \ stopping parameter:
\ hydrogen column density (commented out)
Appendix B: Luminosity Script

In the following is the verbatim version of a python script used to calculate the total monochromatic luminosity from the Cygnus X-1 input spectrum, as well was for computing estimates of energy output from Cloudy spectra.

```python
# This script calculates the total luminosity from the input spectrum
# and finds the size of the Stroemgen sphere
#
from __future__ import with_statement
from math import pi
from math import log10
# FIND OUT FILENAME #

def ask_file(prompt):
    inputfile=raw_input(prompt)
    return inputfile

# Test if the user wishes to enter lower and upper frequency limits
def ask_limits(prompt, retries=3, complaint='yes or no, please!'):
    while True:
        ok=raw_input(prompt)
        if ok in ('y', 'ye', 'yes'):
            lfreq=ask_lfreq('Please enter the lower frequency limit (float): ')
            ufreq=ask_ufreq('Please enter the upper frequency limit (float): ')
            return lfreq, ufreq, True
        if ok in ('n', 'no', 'nop', 'nope'):
            lfreq=False
            ufreq=False
            return lfreq, ufreq, False
        if retries<0 : raise IOError, 'refusenik user'
        print complaint

# PUT IN LOWER LIMIT TO FREQUENCY
def ask_lfreq(prompt, retries=3, complaint='Please enter a float number!'):
    for i in range(retries):
        lfreq=raw_input(prompt)
        try:
            lfreq=float(lfreq) #test if lfreq is float
        except:
            lfreq= \n            return lfreq #ufreq is float, return
```

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print "Your input was neither float nor integer. Please try again!"
retries = retries -1  # number wasn’t float, Try again!
if retries < 0 : raise IOError, 'refusenik user'
print complaint

# PUT IN UPPER LIMIT TO FREQUENCY
def ask_ufreq(prompt, retries=3, complaint='Please enter a float number!'):
    for i in range(retries):
        ufreq=raw_input(prompt)
        try:
            ufreq=float(ufreq)  # Test if ufreq is float
            return ufreq  # ufreq is float, return
        except:
            print "Your input was neither float nor integer. Please try again!"
            retries = retries -1  # number wasn’t float, try again!
            if retries < 0 : raise IOError, 'refusenik user'
            print complaint

# Convert strings into numbers
def conversion(input):
    # pfreq, plnu= [], []
    freq, lnu, ergs, phot =[], [], [], []
    lfreq, ufreq, ok=ask_limits('Enter lower and upper frequency bounds? yes or no: ')
    print lfreq, ufreq
    with open(input, 'r') as file:
        for line in file:
            number1, number2 = [float(x) for x in line.split()]
            if not ufreq or number1 < ufreq:
                if not lfreq or number1 > lfreq:
                    freq.append(number1)
                    lnu.append(number2)
                    energy=number1*6.62606885e-27
                    ergs.append(energy)
                    photons=number2/energy
                    phot.append(photons)
    # if lfreq==False:
    #    lfreq=pfreq[0]
    # if ufreq==False:
    #    ufreq=pfreq[-1]
    # for i in range(len(pfreq)):
    #    if pfreq[i] < ufreq :
# if pfreq[i-1] > lfreq :
#     freq.append(pfreq[i])
#     lnu.append(plnu[i])
print freq[0], freq[-1]
return freq, lnu, ergs, phot

##############################################

# Lower Limit to the luminosity
def lumlower(freq, lnu, ergs, phot):
    low, lphot=[], []
    low=float()
    for i in range(len(lnu)-1):
        if i<1:
            low=lnu[i]*(freq[i+1]-freq[i]) #this is the first value in the list
            llow.append(low)
            lowph=2*low/(ergs[i+1] + ergs[i])
            lphot.append(lowph)
        else:
            llum=lnu[i]*(freq[i+1] - freq[i])
            low=low+ llum #calculate area under curve
            llow.append(low)
            lowph=lowph+2*llum/(ergs[i+1] + ergs[i])
            lphot.append(lowph)
    return low, llow, lowph, lphot

###############################################

# Upper Limit to the Luminosity
def lumupper(freq, lnu, ergs, phot):
    lup, uphot=[], []
    up=float()
    for i in range(len(lnu)): #set the first value 0, otherwise no freq[i-1]
        if i<1:
            up=0
            upph=0
            lup.append(up)
            uphot.append(upph)
        else:
            ulum=lnu[i]*(freq[i] - freq[i-1])
            up=up + ulum #calculate area under curve
            lup.append(up)
            upph=upph+2*ulum/(ergs[i] + ergs[i-1])
            uphot.append(upph)

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def ask_n(prompt, retries=3, complaint='Please enter a float number!; '):
    for i in range(retries):
        n=raw_input(prompt)
        try:
            n=float(n)  # test if n is float
            return n  # n is float, return
        except:
            print "Your input was neither float nor integer. Please try again!"
            retries = retries -1  # number wasn’t float, Try again!
        if retries < 0 : raise IOError, 'refusenik user'
        print complaint

def stromgen(prompt, phtot, retries=3, complaint='yes or no, please! '):
    while True:
        ok=raw_input(prompt)
        if ok in ('y', 'ye', 'yes '):
            n=ask_n('Please specify a hydrogen number density: ')
            alpha=3.0e-13
            nn=n**(-2/3)
            print nn
            nom=3.0*phtot
            print nom
            den=4.0*pi*alpha
            print den
            sphere=(nom/den)**(1./3.)*nn
            strpc= sphere/3.08568025e18
            print "Stromgen Sphere: " + str(sphere) + " cm or " + str(strpc) + " pc"
            return sphere, True
        if ok in ('n', 'no', 'nop', 'nope '):
            sphere=False
            print "No Stromgen sphere will be calculated."
            return sphere, False
        if retries<0 : raise IOError, 'refusenik user'
        print complaint
def main():
    # lumtot=float()
    # up, low=float(), float()
    # lup, llow=[], []
    # freq, lnu=[], []
    # ulum, llum=[], []
    # lowval, upval=float(), float()
    phtot=float()
    input=ask_file('Please type in the input filename: ')
    freq, lnu, ergs, phot=conversion(input) #putting in the data file
    upval, ulum, upph, uphot=lumupper(freq, lnu, ergs, phot)
    print 'This is the upper luminosity limit: ' + str(upval)
    print 'This is the log of the upper luminosity limit: ' + str(log10(upval))
    print 'This is the upper limit to the number of photons: ' + str(upph)
    lowval, llum, lowph, lphot=lumlower(freq, lnu, ergs, phot)
    print 'This is the lower luminosity limit: ' + str(lowval)
    print 'This is the log of the lower luminosity limit ' + str(log10(lowval))
    print 'This is the lower limit to the number of photons:' + str(lowph)
    lumtot= (lowval + upval)*0.5 # Average of the two luminosities
    phtot= (upph + lowph)*0.5 # average number of photons
    print 'This is the total average luminosity: ' + str(lumtot)
    print 'This is the log of the total average luminosity ' + str(log10(lumtot))
    print 'This is the average number of photons in the specified range: ' + str(phtot)
    sphere, ok = stromgen('Calculate size of the Stromgen sphere? ', phtot)
    return

main()}