Discovering the Spectrum of the Seyfert Galaxy Markarian 4752

Project computer exercises AGN

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Introduction

The spectrum of the Seyfert galaxy Markarian 4752, as observed with a grating spectrometer, is analyzed with the `SPEX` facility developed on SRON, the Netherlands. Various predefined models will be fitted to the spectrum to become information about the nature of this object. Previous observation by INTEGRAL have been improved and the mysteriously broadened emission line will be explained.

1 Markarian 4752

Markarian 4752 is a typical Seyfert galaxy, with a redshift of 0.0040 in the cosmology in which Hubble's parameter $H_0 = 50$ km/s/Mpc. This value, together with the neutral hydrogen column density (measured before using the 21 cm hydrogen line), is very accurate. The neutral hydrogen column density to this source is $1.2 \cdot 10^{24}$ m^{-2}.

Optical observations of the galaxy show a high star formation rate of mainly heavy stars near the nucleus, so we can expect a significantly higher nitrogen abundance. Other elements are expected to have approximately solar abundances, although it is usual to find higher abundances in the innermost regions of the galaxy. Previous optical spectroscopical measurements of the composite stellar spectrum do nevertheless show solar abundances for all elements except nitrogen.

In the past, the source has been observed by the INTEGRAL X-ray detector. This showed a high energy cut-off at 100 keV. The galaxy is a Seyfert galaxy, so it contains an active nucleus with a strong power law continuum. In addition to that continuum there is some soft X-ray emission from the accretion disk. For some not well understood reason, the disk appears to emit preferentially black body radiation at each radius. There are also clear signs of a strong, photo-ionized outflow. Apart from that the disk shows the signatures of a mysteriously broadened emission line. We will try to characterize this line and to derive its physical properties.

2 Instrument

The instrument used is a grating spectrometer similar to the Chandra Low Energy Transmission Grating Spectrometer (although a 100 times larger effective area, but with a lower spectral resolution: 0.08 FWHM). A plot of the effective area can be found in Figure 1. With this instrument the spectrum in Figure 2 is obtained. We will step by step describe the procedure followed to analyze it and to obtain the desired information of this object.

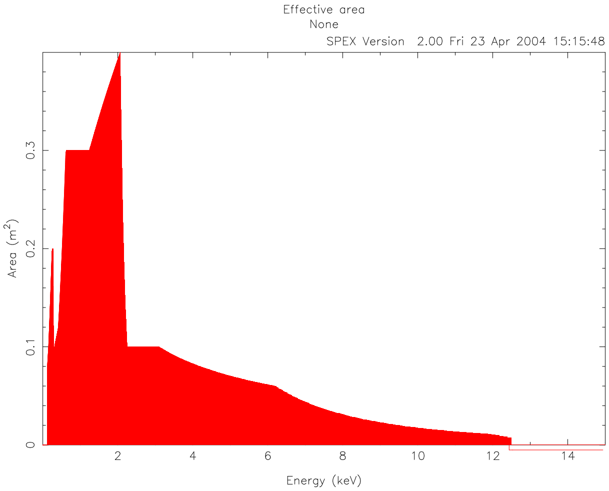

Figure 1: A plot of the effective area of the instrument used

3 The `SPEX` environment

The environment used to analyze this spectrum is called `SPEX` and is developed at SRON, the Nether-

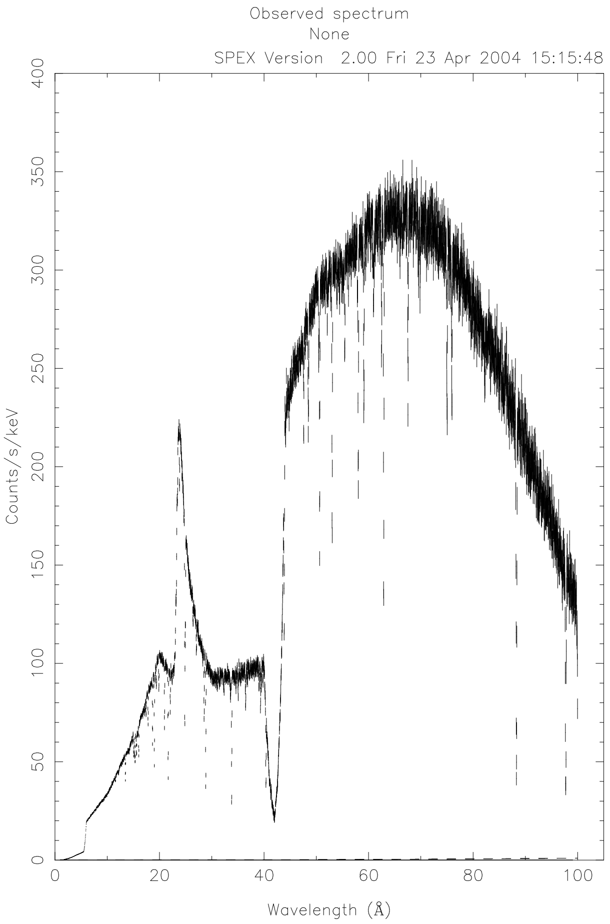

Figure 2: The raw spectrum of Markarian 4752 as obtained with a grating spectrometer

lands. In `SPEX` there are various predefined models which can be fitted to the spectrum. Two kinds of components can be distinguished: *additive* and *multiplicative*. The multiplicative components act on additive components (think for instance of a cosmological redshift (multiplicative component) which acts on the power law spectrum (additive component) of the source.

There are two kinds of additive components. Simple ones, like black body spectra and power laws, and more complicated plasma components which make use of atomic spectral codes. Multiplicative components are divided in three classes: the absorption-type components (like interstellar absorption), redshift-components (like cosmological redshift) and convolutional components (like Gaussian velocity profiles which broaden the emission lines).

4 Reduction of the spectrum

To analyze the spectrum we should first optimize it. Therefore it may be necessary to omit data channels or to rebin the spectrum.

Because of the information of the INTEGRAL observation that there is a high energy cut-off at 100 keV, we omit all data with energies higher than this value. Thereby we loose no information and our fit will not be affected by ‘data’ with a high statistical weight because of their low value (there will be some noise). By omitting this, `SPEX` will fit the model only to the parts of the spectrum with energy lower than 100 keV.

The fits use a χ^2 method to obtain the best fit. Therefore it is very important not to oversample the spectrum. It is desirable that the size of the bins is approximately 3 times smaller than the size of a resolution element. We therefore have chosen not to rebin the spectrum. Only in moments of fitting for example the powerlaw component (where details like absorption lines are not important) we sometimes rebinned to reduce the fitting time. Afterwards the rebinning is cancelled.

5 The model used to fit the spectrum

Now we will first describe the different components used in our model to fit the spectrum. We will describe them in the order of appearance in our fitting process. The physics as well as the parameters in the components will be addressed shortly.

5.1 Power law spectrum

The nucleus of the galaxy emits an intense power law spectrum. That continuum spectrum will be described by the additive `pow`-component. This component describes a spectrum given by

$$F(E) = AE^{-\Gamma}e^{\eta(E)} \tag{1}$$

in which the function $\eta(E)$ is given by

$$\eta(E) = \frac{r\eta + \sqrt{r^2\xi^2 + b^2(1-r^2)}}{1-r^2} \tag{2}$$

with $\xi \equiv \ln E/E_0$, and E_0, r and b are adjustable parameters. For high energies, ξ becomes large and the approximation $\eta = 2r\xi/(1-r^2)$ will be valid, while for low energies ξ will approach $-\infty$ and as a consequence, η goes to zero. Important parameters in the component are the photon index (Γ), the normalisation and the luminosity.

5.2 Soft X-ray emission from the disk

The soft X-ray component radiated away by the accretion disk is described by a so called disk black body (`dbb`) component, which is also additive. This component describes the radiation losses from a standard Shakura-Sunyeav accretion disk. In such a disk the radiation losses are given by

$$Q = \frac{3GM\dot{M}(1 - \sqrt{r_i/r})}{8\pi r^3} \tag{3}$$

where Q is the radiated energy flux at radius r, M is the mass of the central object, $\dot{M}$ is the accretion rate through the disk an r_i is the inner radius of the disk. If this energy is radiated as a black body, which is assumed to be true, the we can also write Q as

$$Q = \sigma T^4 \tag{4}$$

where the temperature is position dependent: $T = T(r)$ and σ is the constant of Stefan-Boltzmann (3). The total spectrum of such a disk is obtained by integrating over all radii.

The photon spectrum of the disk is given by

$$N(E) = \frac{8\pi^2 E^2 r_i^2 \cos i}{h^3 c^2} f_d(E/kT_i, r_0/r_i) \tag{5}$$

where i is the inclination of the disk (0 for face-on disk, 90 degrees for edge-on disk), E the photon energy, r_0 the outer radius of the disk,

$$T_i^4 = \frac{3GM\dot{M}}{8\pi r_i^3 \sigma} \tag{6}$$

and the function $f_d(y, r)$ is defined by

$$f_d(y, r) = \int_1^r \frac{x\mathrm{d}x}{e^{y/\tau} - 1} \tag{7}$$

where τ, then, is defined by $\tau^4(x) = \frac{1-1/\sqrt{x}}{x^3}$.

Given the fit parameters T_i and r_i, it is easy, with equation 6 to obtain the product $M\dot{M}$, and with use of $r_i = 6GM/c^2$ it is possible to get both M and $\dot{M}$ apart from each other, if the inclination angle is known.

5.3 Broadened emission line

The delta line (`delt`) model is an additive component that gives the option to include emission lines into the model. The line is modeled to have an intrinsic infinitesimal width and its spectrum is given by:

$$F(E) = A\delta(E - E_0), \tag{8}$$

where F is the photon flux in 10^{44} ph s^{-1} keV^{-1}, E is the photon energy in keV, E_0 is the line energy of the spectral line in keV and A is the line normalization in 10^{44} ph s^{-1}. The integrated line flux is thus simply given by A. Instead of the energy the wavelength can also be used as the basic parameter.

The `laor` model is a multiplicative component that can be used to broaden an arbitrary additive component with a relativistic line profile. In our case we use it in combination with the above described delta line model. This component broadens the line, by an amount as can be explained by the relativistic speeds of the source close to the black hole.

$$I(r) \sim 1/(r^2 + h^2)^{q/2} \tag{9}$$

5.4 Absorption in the object itself

`xabs` is taking care of radiation absorbed by a slab of plasma. This model is used here to describe the so called warm absorber. It consist of a wind of plasma ejected from the disk. From this component it is possible to derive abundances of elements, as well as the outflowing speed.

5.5 Redshift

Because we analyze the spectrum of a Seyfert galaxy far away, its light will be redshifted on its journey towards our detector. To take account of this redshift (and possible redshifts due to proper motion, out flowing gas for instance) we use a multiplicative component called `reds`. This component makes a correction for the energy an incoming foton has, as well as for time dilation (because the spectra have units like counts/m^2/s). Of course we need the distance to our source to take account of the cosmological redshift. This distance has a redshift of $z = 0.0040$, as measured before in a cosmology with $H_0 = 50$ km/s/Mpc.

5.6 Interstellar absorption

The light from the Seyfert galaxy is not only redshifted on its travel to the detector on earth, but it travels through the interstellar medium. The ISM contains clouds of neutral hydrogen which absorbs and scatters some of the light. The `absm` component brings this into the model. The important parameter in this component is the column density: the integrated particle density along the line of sight. From previous observations we know that this column density has a value of $1.2 \cdot 10^{24}$ m^{-2}.

6 Analysis of the Markarian 4752 spectrum

The parameters that are fitted by the model have been calculated to have approximately the values as summarized in table 1. For these values the parameters are within two standard deviations of their values. With the calculated parameters, we can now further calculate the properties of the Seyfert galaxy. In Figure 3 the result of the fit can be seen together with the spectrum. When we zoom in to the part from 18 to 24 Angstrom we become figure 4.

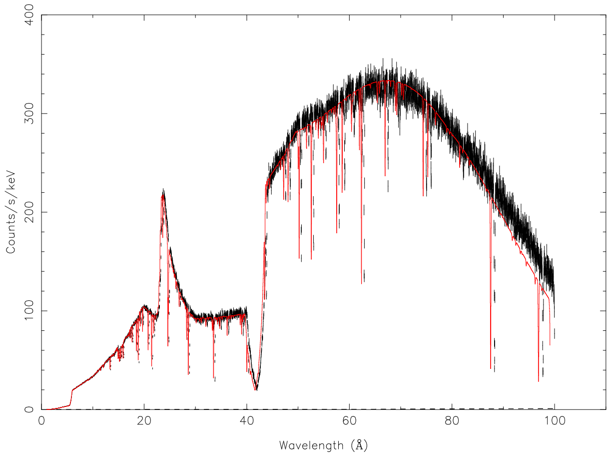

Figure 3: The spectrum and the "best fit", as a result of the described model.

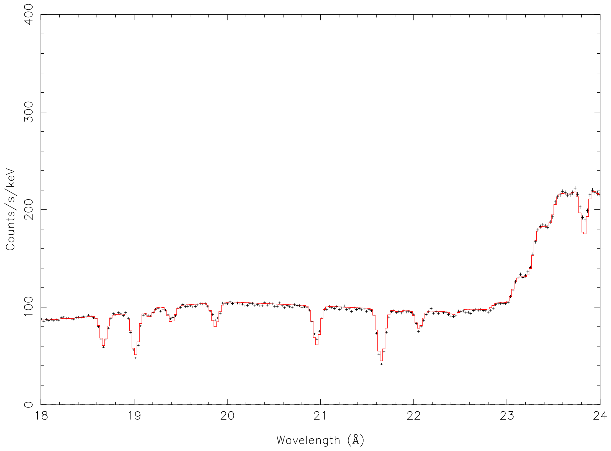

Figure 4: A part of our best fit.

The broadened line with a wavelength of 24.78Å is emitted by the N VII ions in the active nucleus of the galaxy. From the disk black body spectrum and the line broadening, we can derive the mass and accretion rate of the black hole from the luminosity. The luminosity gives us the rate at which mass is accreted onto the black hole. Given an efficiency factor for a black hole of $\eta = 0.057$, which is the efficiency with which mass is converted to energy, the luminosity is given by

$$L = \eta \dot{M} c^2 \tag{10}$$

Adding the luminosities of the different models, the `SPEX`-fit gives us a total luminosity of $L = 1.52 \cdot 10^{36}$ W. Approximating the velocity of light by $c = 3.00 \cdot 10^8$ m/s, we get a mass-accretion rate of

$$\begin{aligned} \dot{M} &= \frac{L}{\eta c^2} = \frac{1.52 \cdot 10^{36}}{0.057\ (3.00 \cdot 10^8)^2} \qquad (11) \\ &= 2.96 \cdot 10^{20} \text{ kg/s} \\ &= 3.13 \cdot 10^{-3} \text{ M}_\odot/\text{yr} \end{aligned}$$

In the disk black body model the inclination angle of the disk is needed to calculate the photon spectrum and the normalization area A. The angle can be calculated from the relativistic line broadening and is fitted by the `Laor` component of the model to be:

$$i = 35^\circ. \tag{12}$$

This model also has fitted the inner radius and it is calculated to be:

$$r_i = \frac{6GM}{c^2} \tag{13}$$

This value for the inner radius is the innermost value of a stable circular orbit around a non-rotating black hole. We can thus conclude that the black hole in the centre of Mrk 4752 is not rotating.

With this, the soft X-ray emission from the disk gives us a disk temperature of

$$\begin{aligned} T_i &= 4.719\text{keV} \qquad (14) \\ &= 5.48 \cdot 10^2\text{K} \end{aligned}$$

By equation 6 and the values of $\dot{M}$, r_i, T and the relation 10, we can calculate the mass M of the central black hole:

$$\begin{aligned} M &= \left(\frac{3c^6 \dot{M}}{8\pi 6^3 G^2 \sigma} \right)^{1/2} \qquad (15) \\ &= \left(\frac{3Lc^4}{8\pi 6^3 T^4 G^2 \sigma \eta} \right)^{1/2} \\ &= 2.29 \cdot 10^{42}\text{kg} \\ &= 7.64 \cdot 10^{11}\text{M}_\odot \end{aligned}$$

The maximal relative thickness of the disk around a non-rotating black hole is at a radius of $r =$

Table 1: Best fit parameters from SPEX calculation

component	parameter	parameter description	value
dbb	norm	Area (10^{16} m^2	$2.1313213 \cdot 10^4$
dbb	t	Temperature (keV)	$4.7195215 \cdot 10^{-2}$
dbb	rout	$\mathrm{R_{out}}$ / $\mathrm{R_{in}}$	$9.1751038 \cdot 10^2$
dbb	ener	$\mathrm{E_r}$ (keV)	1.0000000
dbb	rav	$\mathrm{R_e}$ / $\mathrm{R_{in}}$ at $\mathrm{E} = \mathrm{E_r}$	1.0000000
reds	z	Redshift	$4.0000002 \cdot 10^{-3}$
absm	nh	Column (10^{28} m^{-2})	$1.2000000 \cdot 10^{-4}$
absm	f	Covering fraction	1.0000000
pow	norm	Norm (10^{44} ph s^{-1} keV^{-1})	$1.2111859 \cdot 10^7$
pow	gamm	Photon index	1.7310312
pow	e0	Break energy (keV)	$1.0000000 \cdot 10^{10}$
pow	type	Type of norm	0.0000000
pow	elow	Low flux limit (keV)	$1.0000000 \cdot 10^{-1}$
pow	eupp	Upp flux limit (kev)	$1.0000000 \cdot 10^1$
pow	lum	Luminosity (10^{28} m^{-2})	$9.5189731 \cdot 10^5$
xabs	nh	X-Column (10^{28} m^{-2})	$5.4584618 \cdot 10^{-4}$
xabs	xil	Log ξ (10^{-9} Wm)	1.4295009
xabs	fcov	Covering fraction	1.0000000
xabs	v	RMS velocity (km s^{-1})	$1.3600984 \cdot 10^2$
xabs	rms	RMS blend (km s^{-1})	0.0000000
xabs	dv	Velocity separation (km s^{-1})	$1.0000000 \cdot 10^2$
xabs	zv	Averag velocity (km s^{-1})	$-4.9809723 \cdot 10^2$
xabs	ref	Reference atom	1.0000000
xabs	01	Abundance H	1.0000000
xabs	02	Abundance He	1.0000000
xabs	06	Abundance C	1.0000000
xabs	07	Abundance N	$1.0000000 \cdot 10^1$
xabs	08	Abundance O	1.0000000
xabs	10	Abundance Ne	1.0000000
xabs	11	Abundance Na	1.0000000
xabs	12	Abundance Mg	1.0000000
xabs	13	Abundance Al	1.0000000
xabs	14	Abundance Si	1.0000000
xabs	16	Abundance S	1.0000000
xabs	18	Abundance Ar	1.0000000
xabs	20	Abundance Ca	1.0000000
xabs	26	Abundance Fe	1.0000000
xabs	28	Abundance Ni	1.0000000
delt	norm	Norm (10^{44} ph s^{-1})	$3.3283718 \cdot 10^6$
delt	e	Line energy (keV)	$5.0033998 \cdot 10^{-1}$
delt	type	Type of e	0.0000000
delt	w	Wavelength (Å)	$2.4779999 \cdot 10^1$
laor	r1	Inner radius (GMc^{-2})	6.0000000
laor	r2	Outer radius (GMc^{-2})	$4.0000000 \cdot 10^2$
laor	q	Emissivity slope	2.8390002
laor	h	Emissivity scale	0.0000000
laor	i	Inclination (degree)	$3.5000000 \cdot 10^1$

$2.25\ r_i = 13.5GM/c^2$, and knowing the central mass, can be given by:

$$\begin{aligned} h/r &= \frac{GM\dot{M}}{T^4\sigma R^3 \pi 8} \\ &\approx 0.51 \end{aligned} \tag{16}$$

The luminosities of the different components of the model are:

$$\begin{aligned} L_{\text{pow}} &= 9.52 \cdot 10^{35} \\ L_{\text{dbb}} &= 5.47 \cdot 10^{35} \\ L_{\text{line}} &= 2.67 \cdot 10^{34} \end{aligned} \tag{17}$$

The Eddington luminosity for this mass is:

$$\begin{aligned} L_{\text{Edd}} &= 1.3 \cdot 10^{31} (M/M_\odot) \\ &= 9.93 \cdot 10^{42}\ \text{W} \\ &= 2.54 \cdot 10^{16} \end{aligned} \tag{18}$$

The total luminosity is only a small fraction ($\sim 10^{-7}$) of the Eddington luminosity. This seems to be much too low. A possible explanation is our very low value for the accretion rate (equation 11).

The spectrum also shows some strong absorption lines. Because of the high starburst rate at the galactic center the abundancy of nitrogen is enriched. The other abundancies are approximately solar. For four of the strongest absorption lines we looked up the wavelength and which ion was responsible for the absorption. A strong absorption line indicates an optical depth at line centre of the order of 1. Some possibilities for strong absorption at the required wavelength are the following elements:

Table 2: The wavelength, ion, predicted optical depth at line center, equivalent width and transsition of 4 of the strongest absorption lines in the spectrum.

λ_{obs} (Å)	Ion	τ (m)	W (Å)	Transition
24.9	N VI	2.99	$3.8 \cdot 10^{-2}$	HES4
50.5	Si X	1.15	$4.6 \cdot 10^{-2}$	BGA
62.76	Mg IX	1.76	$7.43 \cdot 10^{-2}$	BE5A
97.5	Ne VII	1.98	0.12	BE5A

The lines are absorbed in an outflow of photoionized gas, the so-called warm absorber. The mass outflow of the warm absorber can be determined from the ionization parameter ξ. Its logarithm is given from the absorption model in `SPEX`. The velocity in the disk is also fitted in the absorption model. With these parameters we can easily calculate the mass loss in the following way:

$$\xi = \frac{L}{nr^2} \tag{19}$$

$$\begin{aligned} \dot{M}_{\text{w}} &= \Omega m_p n v r^2 \\ \frac{\dot{M}_{\text{w}}}{\Omega} &= \frac{m_p v L}{\xi} \\ &= 1.28 \cdot 10^{22} \text{kg s}^{-1} \text{ster}^{-1} \end{aligned} \tag{20}$$

A reasonable assumption is that this massflow cannot be higher than the accretion rate of mass. The maximum solid angle for the outflow of the photoionized wind can be calculated by equating mass loss and mass accretion rates:

$$\begin{aligned} \Omega &= \frac{\dot{M}}{\dot{M}_{\text{w}}} \\ &= 0.02\ \text{ster} \end{aligned} \tag{21}$$

The bulk of the soft X-ray emission usually comes from the disk at a radius of $10GM/c^2$. The angular velocity can be estimated using the Keplerian rotation approximation which gives a value of:

$$\begin{aligned} v_\phi &= \sqrt{\frac{GM}{r}} \\ &= \sqrt{0.1}c\ \text{m/s} \end{aligned} \tag{22}$$

The period therefore is given by:

$$\begin{aligned} P &= 2\pi \sqrt{\frac{r^2}{GM}} \\ &= 1.12 \cdot 10^9\ \text{s} \\ &= 35.5\ \text{yr} \end{aligned} \tag{23}$$

This is the characteristic timescale in which the disk can vary. This seems to be too long (we expected values in the order of seconds or maybe minutes)...

The radial emissivity profile of the broadened emission line is given by the power law in the Laor model. The slope is given by the parameter q and fitted in the model to $q = 2.839$. The emissivity law is given by equation 9 and can be approximated for large radii by

$$\begin{aligned} I(r) &\sim r^{-q} \\ &\sim r^{-2.839} \end{aligned} \tag{24}$$

The radial profile of the total soft X-ray flux from the disk is scaled with T^4 (equation 4). By equation 6 we see that the emissivity of the disk black body model scales with:

$$\begin{aligned} Q &\sim T^4 \\ &\sim r^{-3} \end{aligned} \tag{25}$$

The profile is quite similar and deviates a little at large radii. The two profiles are plotted together in figure 5 in arbitrary units.

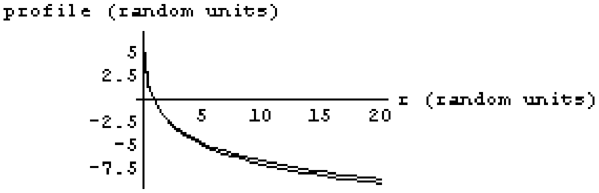

Figure 5: The radial profile of the total soft X-ray flux from the disk and the emissivity profile of the disk black body in arbitrary units. They are clearly not very different.

7 Conclusions

The Markarian 4752 is a typical Seyfert galaxy. The nucleus emits a powerlaw spectrum. In addition the spectrum shows a broad emission line which is emitted near the central black hole, and is therefore relativistically broadened. Furthermore the soft X-ray spectrum shows the black body emission from the disk. The outflowing wind gives rise to some narrow absorption features. Because of the high star formation rate in the core, nitrogen is heavily overabundant.

Table 3: Used constants in SI units

σ	$5.67 \cdot 10^{-8}$ W m^{-2} K^{-4}
$M_\odot$	$3.00 \cdot 10^{30}$ kg
$L_\odot$	3.910^{26} W
m_p	$1.67 \cdot 10^{-27}$ kg
c	$3.00 \cdot 10^{8}$ m/s
G	$6.67 \cdot 10^{-11}$ m^3 kg^{-1} s^{-2}