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Modelling the Extended Narrow Line Region in NGC 1068

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Abstract. We present photoionization models of the high excitation gas in the Extended Narrow Line Region (ENLR) of NGC 1068. The ENLR line fluxes have been calculated allowing for attenuation of the central-source ionizing continuum as a function of distance from the centre. Diffuse continuum emission from low density ENLR gas is included as an important secondary source of ionization. The observed high excitation emission further than 25 arcsec from the centre of NGC 1068 can be fitted by photoionization models using a central-source luminosity of 3.6×10^{44} erg s^{-1} between $10^{14.6}$ and $10^{18.4}$ Hz, with the continuum shape attenuated by nuclear gas with an integrated column density of $N_h = 10^{22}$ cm^{-2}. The reflected soft X-ray continuum from the attenuating gas could be responsible for about 10% of the observed, resolved circumnuclear soft X-ray continuum extending out to 15 arcsec from the centre (Wilson et al 1992).

Key words: galaxies: active – galaxies: nuclei – galaxies: individual (NGC 1068) – galaxies: Seyfert

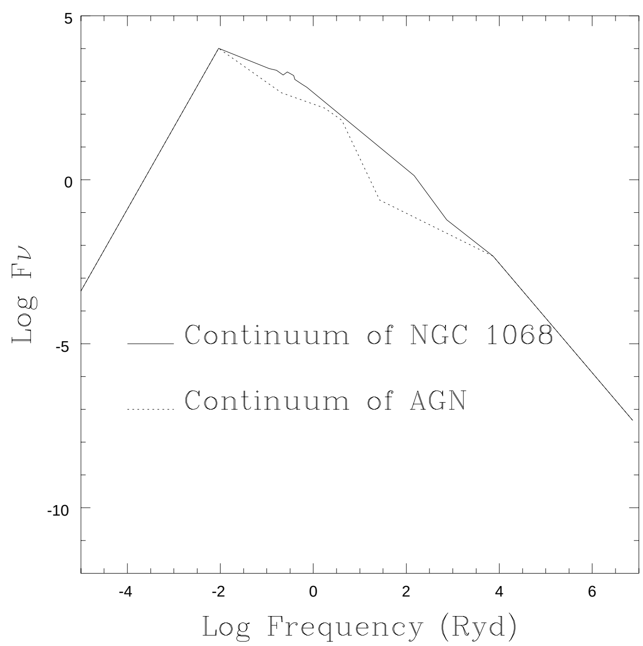

Fig. 1. The adopted continuum of NGC 1068 compared to the canonical AGN continuum of Mathews and Ferland (1987). Both continua are plotted in units of Photons Ryd^{-1} cm^{-2} s^{-1} with arbitrary offsets.

1. Introduction

Spectropolarimetric observations of the Seyfert 2 galaxy NGC 1068 show broad, polarized FeII and Balmer emission lines in the nuclear spectrum (Antonucci & Miller 1985; Snijders et al. 1986; Miller & Goodrich 1990; Miller et al. 1991; Tran et al. 1992). These results suggest that this galaxy actually has a Seyfert 1 nucleus which is obscured from direct view but is seen in light scattered from, and hence polarized by, obscuring material which may be arranged in the form of a disk or torus surrounding the central nucleus.

Inspection of the ENLR spectra shows the existence of ionized gas emitting high-excitation [NeV]λ3425 and [OIII]λ5007 lines at an approximate distance of between 15$''$ and 50$''$ from the centre of NGC 1068 (Evans & Dopita 1986; Bergeron et al. 1989). Lower ionization lines such as [OII]λ3727 and [NII]λ6583 have intensity ratios relative to Hα) which are similar to those seen in HII regions, and do not reflect the degree of ionization which might be expected based on the detection of the [NeV]λ3425 line (Evans & Dopita 1986). Furthermore the spectra of the ENLR show a low intensity of [OIII]λ5007 and HeIIλ4686 lines compared to the intensity of [NeV]λ3425.

Evans and Dopita (1986) modelled the ENLR spectra in NGC 1068 with two emission components: HII regions and highly-ionized low density gas. They also suggested that the continuum seen by the high-excitation gas has a turn-on energy (simulating a photo-electric cut-off due to absorption by intervening material closer to the centre) varying over the range 20-60 Ryd. This decreases the intensity of the HeIIλ4686 and [OIII]λ5007 lines compared to the intensity of [NeV]λ3425. Bergeron et al. (1989) used optical emission-line ratios to in-

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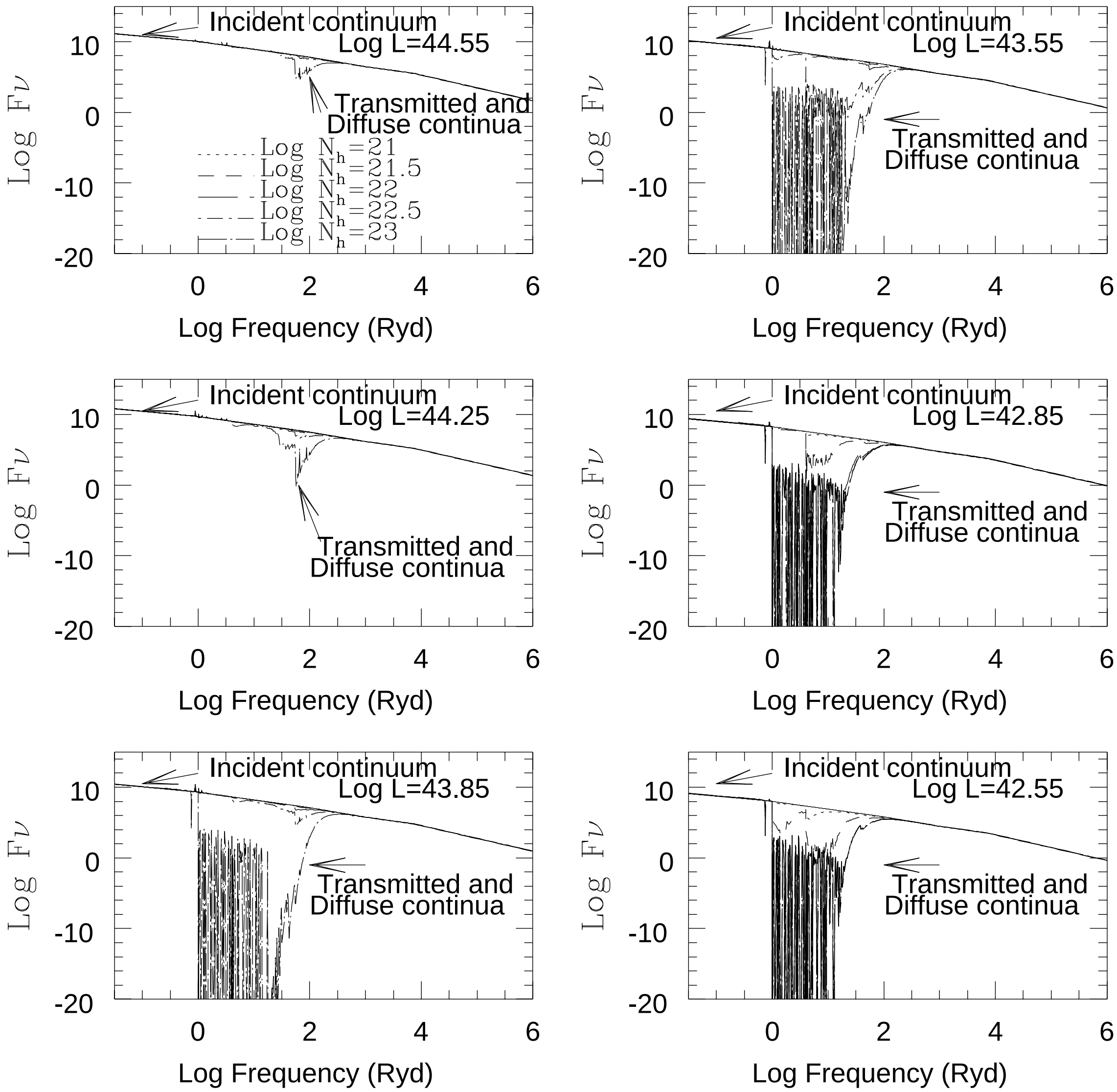

Fig. 2. The unattenuated central-source continuum (labelled incident) together with the sum of the transmitted and diffuse continua for 6 different luminosities of the central-source. Units are Photons $\text{Ryd}^{-1}\ \text{cm}^{-2}\ \text{s}^{-1}$, with an arbitrary constant added to each continuum for display purposes.

fer that the ionizing continuum seen by the ENLR gas may be two orders of magnitude larger than the observed soft X-ray continuum.

Nazarova (1995) modelled the high-excitation ENLR gas in NGC 1068 with a central power-law continuum and an extended source of ionization. The extended source was assumed to be stars of temperature 80 000K located 1–2 kpc from the centre (or 14–28 arcsec adopting 1 arcsec = 72pc (Tully 1988)). The central region of NGC 1068 does have a ring of very luminous HII regions 13 arcsec from the centre (Snijders et al. 1982; Bruhweiler et al. 1991). Adding an additional stellar source changes the shape of the incident spectrum which ionises the ENLR gas by adding a bump at 2.5 Ryd (corresponding to the peak emission energy of a star with temperature 80 000K). This bump changes the population of the ionization stages. The O^{+2} moves to the higher stages O^{+4} and O^{+5} and He^{+} to He^{++}. Similarly Ne^{+4} moves to Ne^{+5}, although this change is small due to the higher ionization threshold. Overall, adding the stellar component leads to stronger emission in [NeV]λ3425 compared to that of [OIII]λ5007 and HeIIλ4686.

Although modelling the ENLR spectra of NGC 1068 with an additional stellar ionization source helps alleviate the “energy deficit” problem, there still exists a problem connected with the geometry of the extended region. Since there are many galaxies with ENLRs which show strong emission in the high-excitation [NeV]λ3425 line (Binette et al. 1996), it seems unlikely that they all have a strong contribution from a ring of very luminous HII regions at just the right location around the nucleus.

Recently, Binette et al. (1996) proposed that the high-excitation line strengths in ENLRs, together with other problems such as low electronic temperatures and the small range in the HeII/Hβ ratio, could be successfully solved by assuming that the ENLR contains a combination of matter-bounded and ionization-bounded clouds. These two cloud populations have different spectra and therefore can be combined to reproduce a wide range of observed ENLR spectra. A principal result was that the ionization-bounded clouds are photoionized by radiation from the central-source which has been attenuated by the matter-bounded component.

In this paper we explore the advantages of such multi-component gas models in attempts to fit the observed ENLR spectrum of NGC 1068, adopting the shape of the central continuum as given by Pier et al. (1994). We also examine the effect of different central luminosities and different amounts of attenuation of these continua on the predicted ENLR spectrum. Models of the observed ENLR emission are discussed in Sect. 2. We examine in Sect. 3 if the model which best fits the ENLR line emission can also explain the observed extended soft X-ray continuum. The conclusions are given in Sect. 4.

2. Modelling the ENLR spectra

2.1. The ionizing continuum

The shape of the central-source continuum in NGC 1068 has been derived from two sources. The UV and X-ray continua ware assumed from Pier et al. (1994), while the rest of the continuum shape was taken to follow that of the canonical AGN continuum given in Mathews and Ferland (1987). These two continua are shown in Fig. 1.

The bolometric flux from the scattering material in the spectral range $10^{14.6}$–$10^{18.4}$ Hz is 1.5×10^{-10} erg cm^{-2} s^{-1} (Pier et al. 1994), corresponding to a luminosity of 3.6×10^{42} erg s^{-1} for an adopted distance to NGC 1068 of 14.4 Mpc (Tully 1988). Adopting this as a minimum central-source luminosity, our photoionization models were calculated within the luminosity range 3.6×10^{42} to 3.6×10^{44} erg s^{-1} (Log L = 42.55–44.55). The luminosity upper limit was chosen to be approximately half the IR luminosity of NGC 1068 ($L_{IR} = 7.3 \times 10^{44}$ erg s^{-1}) found by Telesco and Harper (1980), as about half of the IR emission could be due to dust heated by stars.

2.2. Location of the [Nev] zone

Evans and Dopita (1986) and Bergeron et al. (1989) detected extended high-excitation emission from two knots in NGC 1068 located between 29.4 and 43.5 arcsec and between 24.7 and 40.5 arcsec north-east of the centre. Apart from these, there is also a small [NeV] emission patch in the south-west between 18.2 and 28.8 arcsec from the centre. However the strong [OIII] emission extends further out than the Balmer emission, and is detected up to 45 arcsec from the centre (Bergeron et al. 1989). In our calculations we have adopted a location for the high-excitation ENLR region in NGC 1068 (henceforth called the [NeV] zone) between 25 and 45 arcsec from the centre (or between 1.8 and 3.24 kpc).

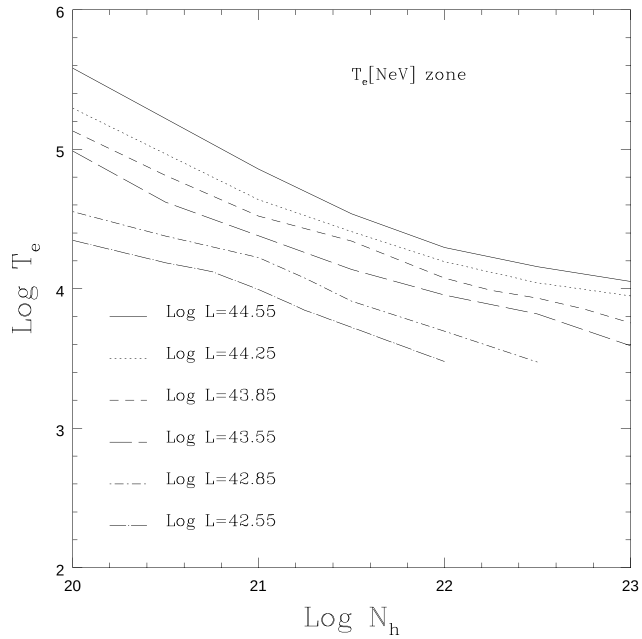

Fig. 3. The electron temperature profiles for a homogeneous envelope of low density gas in the [NeV] zone for different luminosities of the central-source.

2.3. Method

All calculations were carried out using CLOUDY (version c90.01; Ferland 1991) for a plane-parallel slab of gas with solar abundances. Because the high-excitation emissivity in the ENLR depends strongly on the shape of the ionizing continuum, we calculated the line fluxes taking into account the attenuation of the ionizing continuum by gas at radii between 5 and 25 arcsec from the centre (Sect. 2.4; Nazarova et al. 1997). The transmitted portion of the central-source continuum and the diffuse continuum (emitted by the low density gas) were calculated for 6 different luminosities of the central-source within the luminosity range given in Sect. 2.1, with 5 different column densities and different corresponding gas densities. The sum of the transmitted continuum plus the diffuse continuum was then taken as the incident continuum at the starting radius of the [NeV] zone (25 arcsec from the centre). The shape of the unattenuated, central-source continuum and the sum of the transmitted and diffuse continua are shown in Fig. 2. The shape of the attenuated continua depend on both the luminosity of the central-source and the column density of the attenuating gas. The attenuation is large in the EUV/soft X-ray range when the gas is effectively ionization bounded for the dominant absorption species.

It should be noted that the shape of the sum of the transmitted and diffuse continua is quite different from the transmitted continuum alone. Adding the locally-emitted diffuse continua reduces the depth of the gap in the continuum between approximately 1 and 100 Ryd. The emission of the high-excitation [NeV]λ3425 and [OIII]$\lambda\lambda$4959, 5007 lines depend on the shape of the continuum in this region as it controls the parent ion pop-

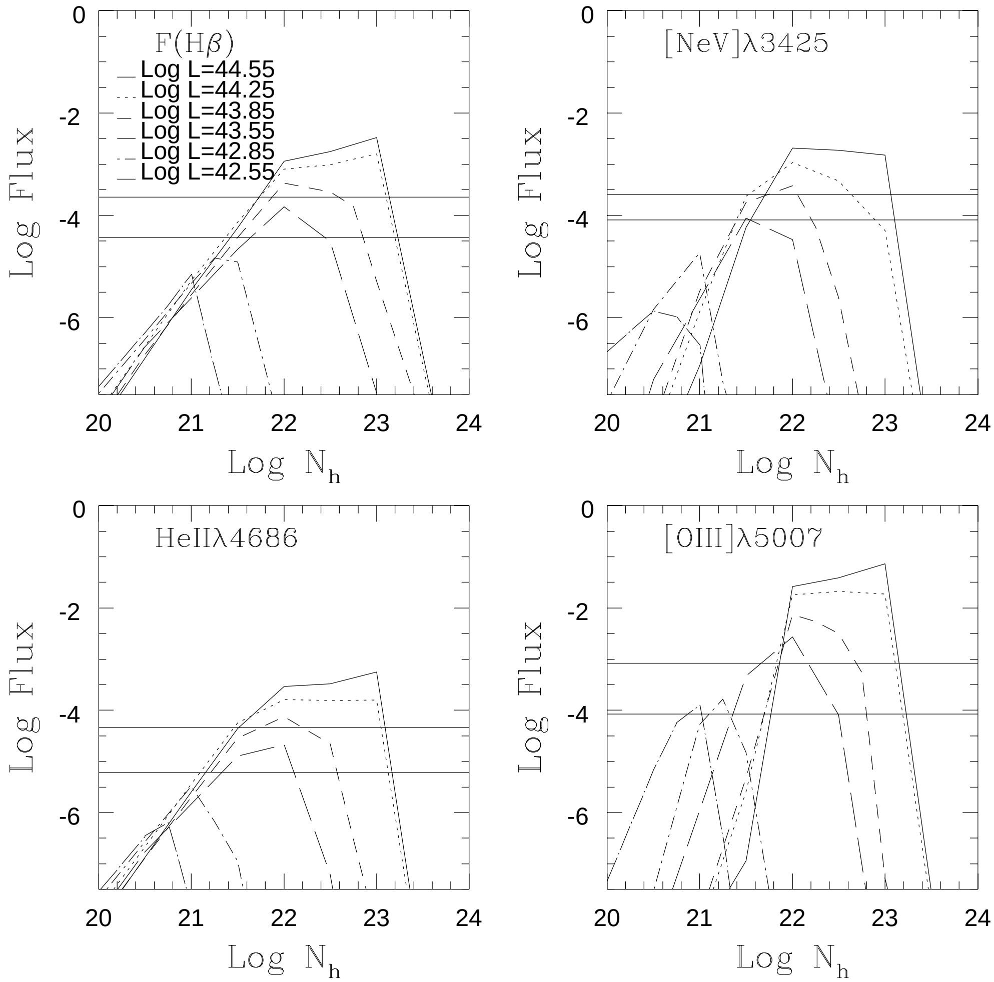

Fig. 4. The theoretical fluxes of the Hβ, HeIIλ4686, [NeV]λ3425 and [OIII]λ5007 lines (in units of erg cm^{-2} s^{-1} at the ENLR) from low density gas in the [NeV] zone versus column density for different luminosities of the central-source.

ulations. The electron temperature of the [NeV] zone is shown in Fig. 3 for different luminosities of the central-source. The sharp drop in temperature after column densities 10^{22} cm^{-2} and $10^{22.5}$ cm^{-2} respectively for low luminosities (Log L = 42.55–42.85) is not shown. For high luminosities (Log L = 43.85–44.55) the temperature remains high enough to produce strong emission in the high-excitation lines even for high column densities (N$_h$ = 10^{22-23} cm^{-2}).

2.4. Attenuating gas geometry

Since we use in our calculations the sum of the transmitted and diffuse continua as the incident continuum for the [NeV] zone, we need to consider the geometry of the gas which attenuates the central-source continuum. As the physical size of the region containing the attenuating gas is fixed (5–25 arcsec from the centre), varying its total column density N$_h$ between 10^{20} and 10^{24} cm^{-2} implies a variation in gas density between 0.023 and 234 cm^{-3}, assuming the gas is homogeneously distributed and that the filling-factor remains the same. The starting radius for the region containing the attenuating gas has been taken to be 5 arcsec, as this is believed to be the maximum size of the region containing the material obscuring the central-source from direct view (Pier et al. 1994). The contribution from scattered central continuum to the illumination of the [NeV] zone depends on the optically thickness for electron scattering (τ_{scat}). The scattered continuum will also be absorbed in the gas with corresponding optical thickness (τ_{absorb}). As τ_{scat} is 10^{-10} times less than τ_{absorb} we can neglect the contribution of the scattered continuum to the shape of the ionizing continuum for the [NeV] zone.

2.5. Low density gas in the ENLR of NGC 1068

The high-excitation [NeV]λ3425 line and part, possibly most, of the [OIII]λ5007 and HeIIλ4686 lines beyond 25 arcsec are produced by highly-ionized, low density gas in the ENLR. The emission from low density gas in the [NeV] zone corresponding to various total column densities is shown in Fig. 4 for different luminosities of the central-source. The two parallel lines show the observed ratios in the line intensities for different parts of the ENLR of NGC 1068 derived from Evans and Dopita (1986) and Bergeron et al. (1989). From Fig. 4 it appears that the observed line fluxes could be fitted with a luminosity of the central-source higher than Log L = 43.85.

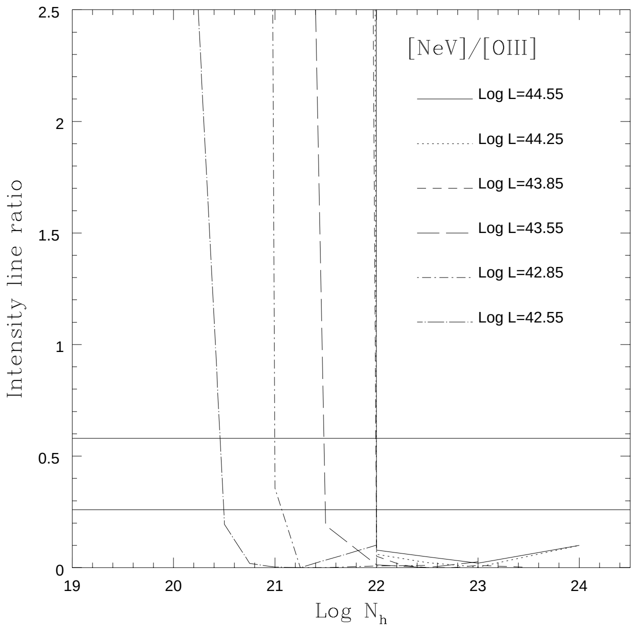

Fig. 5. The theoretical and observed [NeV]λ3425/[OIII]λ5007 line ratio versus column density for different luminosities of the central-source.

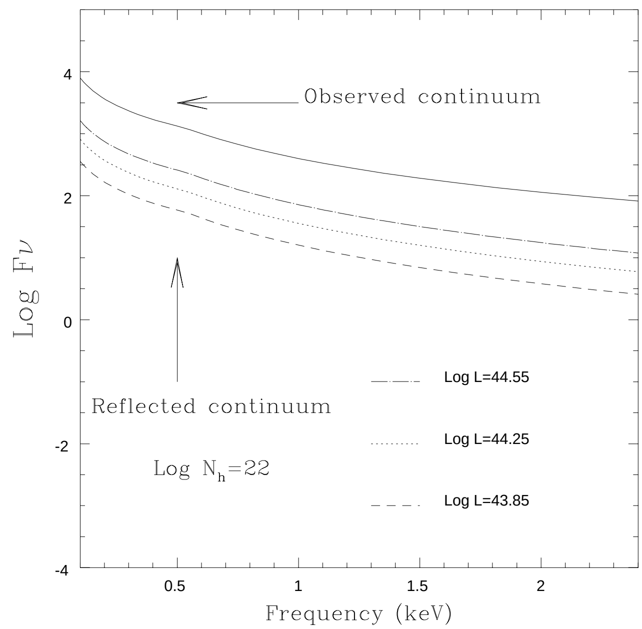

Fig. 6. The observed, resolved continuum and model reflected soft X-ray continua within 15 arcsec. The continua are plotted in Photons Ryd^{-1} cm^{-2} s^{-1} on an arbitrary scale.

Adding emission from high density gas, which could explain the observed low ionization line emission (discussed below), will increase the emission in the Hβ, [OIII]λ5007, and HeIIλ4686 lines, but makes little contribution to the emission in [NeV]λ3425. Therefore, we rule out luminosities below Log L = 43.85 as they fail to explain the minimum observed flux in [NeV]λ3425 even with a filling-factor of 1. For luminosities higher than Log L = 43.85 the filling-factor in the [NeV] zone might be less than 1 in order to fit the observed line intensities.

We note that the predicted [NeV]λ3425 flux is lower than [OIII]λ5007 for all luminosities, in agreement with the observed F(λ3425)/F(λ5007) line ratio which varies between 0.26 and 0.58 in different parts of the ENLR (Bergeron et al. 1989). As can be seen in Fig. 5, a small change in column density produces a quite dramatic change in the F(λ3425)/F(λ5007) ratio. This is due to the approximately 1.7 times higher photon energy needed to produce [NeV] than [OIII]. Hence the former is more sensitive to the column. The observed F(λ3425)/F(λ5007) ratio can be fitted for a small range of "critical" column densities from $10^{20.5}$ cm^{-2} to 10^{22} cm^{-2} for the luminosity range considered here.

2.6. Two-component model of the [Nev] zone

The presence of strong emission in low ionization lines such as Hβ, [OII]λ3727, [OI]λ6300, [NII]$\lambda\lambda$6548, 6583, and [SII]$\lambda\lambda$6717, 6731 indicates emission from low filling-factor high density gas, similar to HII regions, in the ENLR of NGC 1068. This emission is in addition to that from low density gas. The emission from high density gas was therefore also calculated for the 6 different luminosity models. Because the most probable column density obtained from analysis of the low density gas is $N_h = 10^{22}$ cm^{-2} (Fig. 5), the sum of transmitted and diffuse continua for this column density was used to calculate the continuum incident on the high density gas in the [NeV] zone.

Composite photoionization models for three luminosities of the central-source are given in Table 1. The observed and predicted line fluxes in the [NeV] zone from 1 cm^2 of the surface (the surface brightness scaled to the distance of the [NeV] zone) are given together with the relative contributions of the high (HDG) and low (LDG) density gas (HDG/LDG) to the Hβ flux, their densities (Log N_e(LDG) and Log N_e(HDG)) and the filling-factor f for the [NeV] zone. The filling-factor was estimated by comparison of the observed and predicted Hβ flux. Table 1 shows that most appropriate luminosity for the prediction of the observed line fluxes is Log L = 44.55.

Binette et al. (1996) note that all of the NLR photoionization models which fit the strong emission lines predict an [OIII]λ4363/[OIII]λ5007 ratio < 0.01, which is smaller than the observed ratio ~ 0.015. The electron temperature obtained from the observed [OIII]λ4363/[OIII]λ5007 ratio is often higher than the equilibrium temperature of models calculated with densities less than 10^4 cm^{-3}. In our models this line ratio is 0.0157 for a luminosity Log L = 44.55, consistent with the typically observed ratio.

If we suggest a higher luminosity than Log L = 44.55 for the central-source it increases the emission in the high-excitation lines and simultaneously decreases the emission in [OI]λ6300. However it seems unreasonable to increase the proposed luminosity of the central-source more than the observed IR luminosity of Log L_{IR} = 44.88 (Telesco & Harper 1980). Therefore we believe that the best fit for the observed ENLR spec-

Table 1. The logarithms of the observed surface brightness of emission lines scaled to the distance of the [NeV] zone and the modelled lines fluxes (in units of erg cm^{-2} s^{-1}) for three values of the luminosity of the central-source.

λ	Ion	Observed	Log L= 44.55	Log L = 44.25	Log L = 43.85
3425	[NeV]	−3.59 – −4.09	−4.18	−4.30	−4.42
3727	[OII]	−3.29 – −4.10	−4.10	−4.22	−4.76
3869	[NeIII]	−3.80 – −4.50	−4.28	−4.10	−4.35
4363	[OIII]	≤−4.30 – −5.45	−4.88	−4.97	−5.12
4686	HeII	≤−4.34 – −5.21	−4.97	−5.00	−5.10
4861	Hβ	−3.63 – −4.43	−4.11	−4.13	−4.06
4959	[OIII]	−3.77 – −4.34	−3.54	−3.53	−3.59
5007	[OIII]	−3.08 – −4.07	−3.08	−3.08	−3.13
6300	[OI]	≤−4.60 – −5.30	−4.11	−4.23	−3.33
6548	[NII]	−3.95 – −4.82	−4.42	−4.50	−4.73
6563	Hβ	−3.28 – −4.99	−3.61	−3.70	−3.59
6583	[NII]	−3.45 – −4.17	−3.95	−3.70	−4.25
6717	[SII]	−3.96 – −4.70	−4.11	−4.22	−4.28
6731	[SII]	−4.18 – −5.07	−3.94	−4.00	−4.10
HDG/LDG			1	1	1
Log N_e(HDG)			4	4	4
Log N_e(LDG)			0.37	0.37	0.37
Log f			−1.50	−1.33	−1.00

HDG/LDG - The relative contributions from High and Low density gas to the Hβ flux;
N_e(LDG) - The density of Low density gas in units cm^{-3};
N_e(HDG) - The density of High density gas in units cm^{-3};
f - The filling-factor.

tra in NGC 1068 corresponds to a central-source luminosity of Log L = 44.55.

3. The reflected continuum

Investigation of the NGC 1068 nuclear region in soft X-rays (Wilson et al.,1992) shows 3 X-ray sources; unresolved emission associated with the Seyfert nucleus (55% of the total soft X-ray flux); resolved, circumnuclear emission extending from the centre to a distance of 15 arcsec (23%); and large-scale emission up to 60 arcsec (22%), which has a morphology and spatial scale similar to that of the starburst disk. As electrons or dust in the ENLR could reflect some of the central-source continuum into our line of sight (Heckman et al. 1995; Cid Fernandes & Terlevich 1995; Tran 1995), it is interesting to see how much of the circumnuclear soft X-ray continuum could be nuclear emission scattered from the proposed attenuating gas with column density $N_h = 10^{22}$ cm^{-2}.

We used CLOUDY to calculate the reflected continuum for different luminosities. We assume the reflected continuum is the continuum emitted from the illuminated face of the cloud back in the direction of the central-source (i.e. into 2π sr). For a plane-parallel slab the proportion of the reflected continuum in the direction to the observer could vary from $\sim$ 0.5 (when the ENLR is located in the plane of the sky) to zero (when we see the nucleus through the ENLR). The optical images imply that the galaxy disk, and therefore presumably the ENLR gas, inclination is $40^o \pm 3^o$ (Brinks et al. 1997). This implies that the fraction of the reflected continuum in the direction of the Earth is $\approx$ 0.4.

The intensity of the reflected continuum depends on both the luminosity of the central continuum and the column density of the scattering medium. As the column density grows with distance from the centre we expect that the contribution of the scattered light should also increase with distance.

The reflected continua calculated by CLOUDY for the various models are presented in Fig. 6. In each case the reflected continuum comprises the scattered central-source continuum plus the diffuse continuum emitted by the gas. If the central-source luminosity in NGC 1068 is Log L = 44.55 then about 10% of the observed, soft X-ray emission from the circumnuclear component extending to a distance of about 15 arcsec could be due to reflected continuum from a column density $N_h = 10^{22}$ cm^{-2}. The majority of the extended soft X-ray continuum in NGC 1068 would be due to a different origin, possibly the 10^6–10^7 K gas seen in the ROSAT HRI soft X-ray image. This gas could result from a hot outflowing wind driven by the putative central hard X-ray source, or through shocks driven by the radio jets (Wilson & Elvis 1997).

4. Conclusions

The extended high-excitation emission observed between 25 and 45 arcsec from the centre in NGC 1068 (the [NeV] zone) has been modelled with a combination of low and high density gas illuminated by a central ionizing source. Before illuminating the high-excitation gas the continuum is attenuated by gas located within 25 arcsec. The best fit model has a central-source luminosity between $10^{14.6}$ and $10^{18.4}$ Hz of 3.6×10^{44} erg s^{-1}, a low density gas component with Log N_e = 0.37 and a high density gas component with Log N_e = 4. From analysis of the fluxes of the high-exitation emission lines, we find that the attenuating gas between the centre and the high-excitation region has an integrated column density of $N_h = 10^{22}$ cm^{-2}. The reflected soft X-ray continuum from this attenuating gas could explain up to 10% of the observed, circumnuclear soft X-ray emission identified by Wilson et al. (1992) extending from the centre out to a distance of about 15 arcsec.

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