CONSTRAINING THE EXTRA HEATING OF THE DIFFUSE IONIZED GAS IN THE MILKY WAY

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Received 2004 November 5; accepted 2005 June 21

ABSTRACT
The detailed observations of the diffuse ionized gas through the emission lines Hα, [N II], and [S II] in the Perseus arm of our Galaxy by the Wisconsin Hα Mapper (WHAM) survey challenge photoionization models. They have to explain the observed rise in the line ratios [N II]/Hα and [S II]/Hα. The models described here are the first to consider the detailed observational geometry toward the Perseus arm. The models address the vertical variation of the line ratios up to a height of 2 kpc above the midplane. The rising trends of the line ratios are matched. The increase in the line ratios is reflected in a rise in the temperature of the gas layer. This is due to the progressive hardening of the radiation going through the gas. However, extra heating in addition to photoionization is needed to explain the absolute values. Two different extra-heating rates are investigated, which are proportional to $n^0$ and $n^1$. The models show that a combination of both is best to explain the data for which the extra heating independent of density is dominant for $z > 0.8$ kpc.

1. INTRODUCTION
Containing typically half the mass of ionized hydrogen in galaxies, the diffuse ionized gas (DIG) is visible as an extended Hα-emitting layer in our Galaxy (e.g., the WHAM survey) and in many other galaxies (see, e.g., Tüllmann & Dettmar 2000; Collins & Rand 2001; Otte et al. 2001; Hoopes & Walterbos 2003). Studies of emission-line ratios such as [N II]/Hα and [S II]/Hα provide information about the physical conditions of the gas. Simple energy estimations (Reynolds 1990, 1993) favor O and early B stars as the ones responsible for most of the DIG. Three-dimensional models using various methods (e.g., Miller & Cox 1993; Dove & Shull 1994; Wood & Loeb 2000; Ciardi et al. 2002; Wood et al. 2004) showed that it is possible for ionizing photons from O stars to penetrate from the midplane into the halo. Wood & Mathis (2004) noted that the line ratios increase with distance from the midplane due to the progressive hardening of the radiation. So far no specific attempts have been made to use photoionization models to model the trends of the line ratios. Mathis (2000), Domgörgen & Mathis (1994), Sembach et al. (2000), and Bland-Hawthorn et al. (1997) used volume-average models to explain the observed data. The analytical approach by Haffner et al. (1999), hereafter Haffner99 treated the dependence of the line ratios with height. Haffner99 and the further application of this approach to other galaxies by, e.g., Collins & Rand (2001),Otte et al. (2001), and Miller & Veilleux (2003) gave evidence that an additional heating source is needed to explain the rise of the line ratios with increasing distance $z$ from the midplane.

We are constructing photoionization models in order to examine the trends in the observed line ratios and determine whether photoionization can heat up the gas sufficiently to explain the data. We introduce specific extra-heating terms (by “extra” we mean in addition to photoionization) and discuss their properties. In § 2 we introduce the observations of the Perseus arm to which our models are compared. Section 3 deals with the model parameters and discusses geometry and the sight line effects that have been taken into account. The models are compared with the data in § 3.2. Section 4 summarizes the results.

2. DATA OF THE PERSEUS ARM
We use data taken from the WHAM survey (e.g., Haffner99; Hafner et al. 2003), which were kindly provided by R. Reynolds and M. Haffner. The WHAM survey mapped the northern sky in Hα with declinations of $\delta > -30^\circ$. The Perseus arm ($-35^\circ < \delta < -11^\circ$ and $120^\circ < l < 150^\circ$) was additionally mapped in [N II] $\lambda$6583 and [S II] $\lambda$6716. At each pointing an averaged spectrum with a beam of $1^\circ$ was measured, with a velocity resolution of 12 km s$^{-1}$. The emission of the Perseus arm can be separated in velocity space from the local emission (Haffner99) for Galactic longitudes $120^\circ < l < 150^\circ$. This was performed by integrating the line emission in the velocity range $-100$ km s$^{-1} < v < -20$ km s$^{-1}$; no line fitting was performed. We use the intensity of the Hα line, as well as the line ratios [N II]/Hα and [S II]/Hα. The sensitivity limit of 0.1 rayleighs$^2$ results in an observed vertical height of up to $|z| = 2$ kpc, assuming a distance to the arm of 2.5 kpc.

3. MODEL PARAMETERS
We use the spectral simulation code CLOUDY (ver. 96.00; described by Ferland 2002, 2000; Ferland et al. 1998) to model the DIG. CLOUDY determines the physical conditions by balancing the heating and cooling rates, so that the energy is conserved. The results of the models are compared to the observed emission-line ratios [N II]/Hα and [S II]/Hα and the gas temperature as derived from [N II]/Hα.

In order to realize a model describing the DIG, certain parameters have to be specified. The ionizing spectrum of the source is composed of three different stellar temperatures: 56% from $T = 35,000$ K, 12% from $T = 40,000$ K, and 32% from $T = 45,000$ K, as used in Mathis (2000) and Wood et al.

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2 1 rayleigh = $10^9/4\pi$ photons cm$^{-2}$ s$^{-1}$ sr$^{-1}$.
important because extra heating is dominant for large \( z \) heights, we set the ionization structure to remain the same for all models (see Fig. 5). This is in accordance with the idea that the extra heating affects only the temperature of the gas. The forbidden levels of nitrogen and sulphur can then be more easily excited by collisions with the electrons, which in turn elevates the line ratios \([N \, ii]/H\alpha\) and \([S \, ii]/H\alpha\). Figure 1 shows that the intensity gradient of \( H\alpha \) varies only a little for the different models. The scale heights for the models are slightly different (\(<10\%\)) for the models with extra heating, which can be explained by assuming that the DIG layer is in pressure equilibrium. This effect was also noted by Wood & Mathis (2004). The ionization parameters \((U)\) of all models lie in the narrow range between \( \log(U) = -3.0 \) and \(-3.1\).

The composition of the interstellar medium (ISM) in CLOUDY is used with \( N/H \) and \( S/H \) set to the values in Haffner99 (\( N/H = 7.5 \times 10^{-5}, S/H = 1.86 \times 10^{-5} \)). Graphite and silicate grains with the size distribution used for the ISM (see Hazy; Ferland 2002) are present in the gas and account for less than 10% of the global heating. The inclusion of polycyclic aromatic hydrocarbons gives variations smaller than 3% for the line ratios and has only a small effect on the heating balance. The interaction with cosmic rays is taken into account, as described in Ferland & Mushotzky (1984).

A crucial factor is the consideration of the line of sight. The observations give information about the line ratios at different positions orthogonal to the source of the ionizing radiation. The correct local line ratios are represented by the ratios of the volume emission coefficients \( \epsilon_j \): \( I_j/I_2 = \int d \zeta \epsilon_j(\zeta)/\int d \zeta \epsilon_j \approx \epsilon_j/\epsilon_2 \). An important issue is the treatment of the line of sight to the Perseus arm due to our position in the Milky Way, as shown in Figure 2. Each pointing of the WHAM survey contains contributions from different \( |z| \) heights above the midplane \((|z|)\) and \((|z|)\), and this effect is taken into account by integrating over the particular sight line in the models. The distance to the Perseus arm is assumed to be 2.5 kpc and the thickness of the arm to be 1 kpc, as quoted in Haffner99. Moreover, the observations are the average of a beam size of 1', which means that we have to take into account an additional integration over different \( z \) heights, on average 45 pc. These effects of geometry and observational smearing are taken into consideration here for the first time. Figure 3 shows the effect of beam smearing
and the line-of-sight geometry on the calculated line ratios for \( z \) heights up to 2.5 kpc, which have to be considered for the observed heights of 1.8 kpc. These effects increase the "corrected" line ratios by at most 15%, and their trend is altered for high \( z \) heights. The "corrected" model without an extra heating seems to suggest that \([\text{N} \text{ ii}] / \text{H} \alpha / \text{C} \text{ ii}\) does not increase after about 1.6 kpc, but the "uncorrected" model shows a further increase due to the hardening of the radiation. The result of the gas temperature (\( x \text{.2}; \text{Fig. 4} \)) is even more influenced by this issue. The discussion of the line ratios therefore needs to include an appropriate treatment of the line-of-sight geometry and beam smearing to take these effects into account.

3.1. Extra Heating

Heating in addition to photoionization is included, proportional to \( n^2 \) and \( n^3 \), in accordance with Reynolds et al. (1999; their factors \( G_1 \) and \( G_2 \), respectively). We choose rates in the same range as those in their paper: \( G_1 = 1 \times 10^{-25} \text{ ergs cm}^{-3} \text{ s}^{-1} \) and \( G_2 = 5 \times 10^{-27} \text{ ergs cm}^{-3} \text{ s}^{-1} \). The heating-cooling balance can then be written as either \( G_0 + G_1 / n_e = \Lambda \) or \( G_0 + G_2 / n^2_e = \Lambda \). The heating due to photoionization is given by \( G_0 n_e^2 \), and the cooling by \( \Lambda n_e^2 \). The inclusion of an extra-heating source raises the gas temperature of the models, at the same time as the ionization structure varies only slightly. The temperatures of the CLOUDY models are calculated according to the heating-cooling balance. The extra heating therefore increases the temperature, with more pronounced effects at larger \( z \) heights as the photoionization heating rate decreases as \( n^2 \), as shown in Figure 4. The graph is explained in more detail in the next section.

In our models the ionization structure is nearly unaffected by the inclusion of an extra-heating source, with sulphur slightly more affected than nitrogen, in line with the basic assumption in Reynolds et al. (1999) for the extra heating. However, they assume a constant ratio of \( \text{N}^+ / \text{N} \), whereas the models show a dependence on \( z \) height, which is to be expected as the radiation gets progressively absorbed. Figure 5 shows the ionization structure and the change that is dependent on the different heating rates. Hydrogen is nearly fully ionized throughout all models, which is a basic characteristic of the DIG.

3.2. Comparison with Observations

In Figures 6 and 7 the models differ by the type of extra heating, ranging between models without extra heating and those including an extra heating with a rate of \( G_1 = 1 \times 10^{-25} \text{ ergs cm}^{-3} \text{ s}^{-1} \) and \( G_2 = 5 \times 10^{-27} \text{ ergs cm}^{-3} \text{ s}^{-1} \). There was no fitting done to match the models with the observations.
No “best-fit” exists, and therefore the models are independent of the observational quality, individual spectral features, or small-scale variations that cannot be reproduced with a smooth density distribution. As the data for small $z$ heights are contaminated with radiation from the midplane and dust absorption, it is convenient to consider line ratios for $|z|$ heights above 0.8 kpc to be “pure” DIG. This is also the range for which the H$\alpha$ scale height was determined. The models show lower values of [N ii]/H$\alpha$ and [S ii]/H$\alpha$ for the lower $z$ heights, as doubly ionized nitrogen contributes 35% and doubly ionized sulphur even 80%, as seen in Figure 5. As a consequence, [N ii] and [S ii] are weaker. Figure 6 shows the development of the line ratios with $|z|$ height; both the data and the models show an increase with $|z|$. The trend in the line ratios is matched by the models even without an extra-heating source.

The [N ii]/H$\alpha$ line ratio above 1 kpc can be explained with the models including an extra heating rate. The modeled [S ii]/H$\alpha$ ratio is up to a factor of 2 below the observations. However, the theoretical uncertainty for the [S ii] line is very high, as dielectronic recombination is an important process in the DIG. As the corresponding recombination coefficients are not known (see discussion in Ferland et al. 1998), the results of the models have to be handled with care. Our models use the KLUDGE approximation (Ferland 2002). Models without dielectronic recombination have [S ii]/H$\alpha$ decreased by 50%. If the rate is doubled, then [S ii]/H$\alpha$ is increased by 50%.

Figure 4 shows the gas temperature of the models, with the increase of the line ratios with $z$ height due to the progressive hardening of the radiation as the photons go through the gas layer. To explain the observed line ratios, however, an extra-heating source is needed that does not alter the general shape of the predicted line ratios, but elevates the line ratios. As [N ii] and [S ii] are forbidden lines that get collisionally excited by electrons, an increase in gas temperature increases the amount of electrons capable of exciting the singly ionized nitrogen and sulphur ions, which can then decay by emitting the emission lines in question. The gas temperature is deduced from the observations through the relation (following Reynolds et al. 1999): $I_{[N\text{II}]/H\alpha} = 1.84 \times 10^5 (N^+/N)(H^+/H)^{-1} T_4^{0.39} \exp(-2.18/T_4)$. Assuming that $N^+/N = H^+/H$ and the abundance as stated in § 3 gives $I_{[N\text{II}]/H\alpha} = 13.75 T_4^{0.39} \exp(-2.18/T_4)$. We do not use the collision strength of singly ionized nitrogen from Reynolds et al. (1999) [N$: \Omega(3P, ^1 D) = 2.28 T_4^{0.20}$, Aller 1984] but the data from Stafford et al. (1994) [N$: \Omega(3P, ^1 D) = 3.02 T_4^{0.01}$]. This leads to the different coefficients and temperatures, on average 250 K less than the values of Reynolds et al. (1999). For singly ionized sulfur we use the data from Lanzafame et al. (1993), instead of Aller (1984) as in Reynolds et al. (1999). The plot also shows the impact of the line-of-sight geometry and beam smearing, as well as our consideration of the ionization structure of the models. As the line of sight leads to higher [N ii]/H$\alpha$ ratios (up to 15%), these effects, when accounted for, lower temperatures. The ionization structure, i.e., $N^+/N \approx H^+/H$, is only valid for $z > 800$ pc and leads to higher estimates of the temperature.
The combined effect is to elevate the derived temperature for \( z < 800 \) pc and above that to lower values by about 200 K. The temperatures in models without an extra-heating source are too low, while an extra-heating source independent of density shows very good agreement with the observed temperatures. The extra heating \( \propto n' \) seems to best fit the data up to 800 pc, after which the extra heating \( \propto n^0 \) gives the best agreement for higher \( z \)-values. The interpretation for the \( z \) heights \(< 800 \) pc must be regarded with care, as this region is contaminated by radiation from the mid-plane, making the part responsible for the DIG emission difficult to estimate. Magnetic reconnection (e.g., Birk et al. 1998) or heating by cosmic rays through linear Landau damping (Lerche & Schlickeiser 2001) are possible processes that could produce heating independent of density. As photoelectric heating from dust grains is \( \propto n^1 \), the data suggest that there is more dust present at \( z \) heights below 800 pc than is present in the models if this is the mechanism responsible for the elevated temperature.

In Figure 7 the line ratios \([N \text{ ii}] / \text{H}\alpha\) and \([S \text{ ii}] / \text{H}\alpha\) are plotted against each other. Values of \([N \text{ ii}] / \text{H}\alpha\) greater than 1, which cannot be explained by classical \( \text{H} \text{ ii} \) region calculations, are reached with models using an extra-heating source. Also in this case the extra heating independent of density is able to produce higher \([N \text{ ii}] / \text{H}\alpha\) ratios than the other models, which therefore achieves a better match with the data. The limits of Haffner99 for two constant \( S^+/S\) ratios (0.5 and 0.25) are also given. The ionization fractions of the models (see Fig. 5) are within these two limits for \( z > 0.6 \) kpc. Together with the temperature plot (Fig. 4), the models provide a match in all these direct and derived quantities with the data and agree with the estimates of Haffner99 and Reynolds et al. (1999). The application to other galaxies shows that this diagram is also a valuable diagnostic for chemical evolution (Elwert et al. 2003).

4. SUMMARY

We have shown that the observed trend of the line ratios \([N \text{ ii}] / \text{H}\alpha\) and \([S \text{ ii}] / \text{H}\alpha\) above the Galactic plane can successfully be explained by photoionization models that include extra heating and take into consideration the line-of-sight geometry. The observed values require an extra-heating source with a rate at the lower end of the predicted values of Reynolds et al. (1999), according to our models. At high \( z \) heights (\( z > 800 \) pc) extra heating independent of density gives the best agreement with the data, whereas for smaller \( z \) heights an extra-heating term \( \propto n^1 \) gives better results concerning the temperature. There is an intrinsic increase in the line ratios and the gas temperature due to the progressive hardening of the radiation. The extra-heating terms enhance this trend and elevate the line ratios to the observed values. It is important to incorporate the observed geometry of the Perseus arm into the models when comparing with the data. A discussion concerning models of observed line ratios in edge-on galaxies is given in Elwert (2003) and Elwert & Dettmar (2005).

This work was supported by the Deutsche Forschungsgemeinschaft (DFG) through SFB 591 and by the Deutsches Zentrum für Luft- und Raumfahrt through grant 50 OR 9707. T. E. wants to thank Kenneth Wood and Ron Reynolds for helpful comments and enlightening discussions during the writing of the paper. We also want to thank the anonymous referee for offering many very useful suggestions and comments, which helped to improve the publication.
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