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TEMPERATURE VARIATIONS AND NON-PHOTOIONIZATION HEATING IN THE WARM IONIZED MEDIUM OF GALAXIES

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RESUMEN

Las líneas de emisión observadas en el halo gaseoso de la Vía Láctea y otras galaxias sugieren la existencia de fuentes de calentamiento adicionales—además de la fotoionización—que incrementan la temperatura electrónica en regiones de baja densidad. De hecho estas fuentes están predichas para el medio interestelar. Por ejemplo, la disipación de la turbulencia por la fricción entre partículas neutras y iones así como el calentamiento por efecto fotoeléctrico en granos pequeños, pueden calentar el medio ionizado tibio a una tasa de 10^{-25} n_e ergs cm^{-3} s^{-1}. Estas fuentes, si están presentes, pueden dominar al calentamiento por fotoionización en regiones donde $n_e \lesssim 0.1$ cm^{-3}, produciendo el incremento observado en los cocientes de intensidades de [S II]/Hα y [N II]/Hα a grandes distancias del plano galáctico. La reconección magnética y las interacciones Coulombianas con rayos cósmicos son otras posibles fuentes. Este calentamiento también podría explicar las variaciones de cocientes de líneas observados en NGC 891, incluyendo el incremento con la distancia del plano Galáctico del [O III] λ5007/Hβ, que no puede ser explicado por modelos de fotoionización puros.

ABSTRACT

Optical emission lines observed in the gaseous halo of the Milky Way and other galaxies suggest the existence of a supplemental heat source—in addition to photoionization—that increases the electron temperature in regions of low density. Such heat sources are in fact predicted to exit in the interstellar medium. For example, both the dissipation of turbulence through ion-neutral dampening and photoelectric heating by small grains could heat the warm ionized medium in the Milky Way at the rate of about 10^{-25} n_e ergs cm^{-3} s^{-1}. If such a source were present, it would dominate over photoionization heating in regions where $n_e \lesssim 0.1$ cm^{-3}, producing the observed increases in the [S II]/Hα and [N II]/Hα intensity ratios at large distances from the Galactic midplane. Magnetic reconnection and Coulomb collisions by cosmic rays are other potential sources. This heating rate would also account for the emission line ratio variations observed in NGC 891, including the increase in [O III] λ5007/Hβ with distance from the midplane, which cannot be explained by pure photoionization models.

Key Words: **GALAXIES: ISM — GALAXY: HALO — H II REGIONS — ISM: GENERAL**

1. INTRODUCTION

The warm ionized medium (WIM), also called the diffuse ionized gas, or DIG, is a principal component of the interstellar medium in our Galaxy and others. In the Milky Way it is characterized by warm ($\sim 10^4$ K), low density ($\sim 10^{-1}$ cm^{-3}) regions of nearly fully ionized hydrogen that occupy a significant fraction (20%) of the volume up to a height of 1500 pc or more from the midplane. The source of the ionization and heating of this component is not understood (Reynolds 1995; Rand 1998). Observed optical line intensities, particularly the high values of [S II] λ6716/Hα and [N II] λ6584/Hα compared to those in traditional, discrete H II regions surrounding O and early B stars suggest that photoionization by a dilute radiation field plays an important role (e.g., Domgörgen & Mathis 1994). O stars are the only known source with sufficient power to maintain the WIM, and Miller & Cox (1993) and Dove & Shull (1994), for example, have suggested that Lyman continuum radiation originating from O stars penetrates the H I cloud layer and ionizes diffuse interstellar gas within the disk and lower halo. However, the high opacity of the interstellar H I has led others to propose the existence of more widely distributed sources of ionization (e.g., Slavin, Shull, & Begelman 1993; Mellott, McKay, & Ralston 1988; Sciama 1990; Raymond 1992; Skibo & Ramaty 1993).

Although photoionization models incorporating a low ionization parameter U (the ratio of photon density to gas density) have been generally successful in accounting for the elevated [S II] λ6716/Hα and [N II] λ6584/Hα and low [O III] λ5007/Hα ratios observed in the WIM (e.g., Domgörgen & Mathis 1994; Greenawalt, Walterbos, & Braun 1997; Martin 1997; Wang, Heckman, & Lehnert 1998), the models have failed to explain observed *variations* in some of the ratios. For example, Rand (1998) observed that [S II]/Hα and [N II]/Hα increase with increasing distance $|z|$ from the midplane of NGC 891, having values of 0.2 and 0.35, respectively, near $z = 0$, and 0.6 and 1.0, respectively, near $|z| = 2000$ pc. To account for such large ratios at high $|z|$, Rand had to adopt a hard stellar spectrum (an upper IMF cutoff of 120 $M_\odot$) plus additional hardening as the radiation propagated away from the midplane. However, such a hard spectrum appears to be inconsistent with He I λ5876 recombination line observations (Rand 1998, 1997, and references therein).

The models also cannot account for the fact that, while the variations in [S II]/Hα and [N II]/Hα are large, [S II]/[N II] remains nearly constant. A similar behavior for [S II], [N II], and Hα has been observed in other galaxies (e.g., Golla, Dettmar, & Domgörgen 1996; Otte & Dettmar 1999) as well as in the Milky Way (Haffner, Reynolds, & Tufte 1999). Golla et al. (1996) and Rand (1998) have pointed out that the constant value of [S II]/[N II] cannot be reproduced by photoionization models, because in these models variations in [S II]/Hα and [N II]/Hα are in large part the result of variations in the ionization parameter U, which in turn affects the ionization state of the gas, specifically N^+/N and S^+/S. Because of the different ionization potentials for S and N, variations in U always produce larger changes in S^+/S (i.e., [S II]/Hα) than in N^+/N (i.e., [N II]/Hα).

Finally, pure photoionization models fail to reproduce the observed variations in [O III]/Hβ with increasing $|z|$, or increasing [S II]/Hα and [N II]/Hα (Rand 1998; Greenawalt et al. 1997). In NGC 891, for example, the [O III]/Hβ intensity ratio more than doubles from 0.3 at $z = 0$ to about 0.75 at $|z| = 2000$ pc (Rand 1998). The models predict a *decrease* in the ratio. Rand proposed an additional source of collisional ionization at high $|z|$ to account for the enhanced [O III] intensity, but emphasized that this would still not explain the constancy of [S II]/[N II].

2. EVIDENCE FOR VARIATIONS IN THE ELECTRON TEMPERATURE

It has recently been demonstrated that these observed line ratio variations, which cannot be accounted for by pure photoionization models, could in fact be explained if an additional source of heat were present that dominated over photoionization heating at low densities (Reynolds, Haffner, & Tufte 1999; Haffner et al. 1999). Basically, Haffner et al. (1999) have shown that an increase in T_e from 7000 K at $|z| = 500$ pc to approximately 10,000 K at 1500 pc would produce the observed factor of three increases in the [N II]/Hα and [S II]/Hα ratios observed in the Milky Way. The constancy of [S II]/[N II] is then a natural consequence of the fact that the two lines have nearly the same excitation energy. Such temperature increases would also produce increases in other electron excited transitions, [O III] λ5007, for example, possibly eliminating the need for an increase in the abundance of the ion at high $|z|$ in NGC 891 (see § 4 below).

The emission line data also show that the regions with higher [S II]/Hα and [N II]/Hα ratios are regions not just at larger distances $|z|$ from the galactic midplane, but more generally are regions with lower electron density. This is indicated by the strong anticorrelation between these line ratios and the Hα intensity. This anticorrelation is apparent not only in the data showing increasing ratios with increasing $|z|$, but also in observations at constant $|z|$ (e.g., Rand 1998; Otte & Dettmar 1999; Domgörgen & Dettmar 1997; Golla et al. 1996; Ferguson, Wyse, & Gallagher 1996) and at large Galactocentric radii (Bland-Hawthorn, Freeman, & Quinn 1997). A strong anticorrelation is also found in the observations of the Milky Way (Haffner 1999; Haffner et al. 1999), again, not just with increasing $|z|$, but also for lines of sight that sample only relatively low $|z|$ gas in the local Orion arm. Since these variations in the line ratios appear to be due to variations in T_e, and since it is difficult to see how the integration length could affect the temperature, it appears that variations correlated with Hα intensity are actually variations correlated with density.

A temperature that varies inversely with density would require a supplemental heat source that somehow dominates over ionization heating at low densities. The heating rate per unit volume from photoionization is limited by recombination and is thus proportional to n_e^2. The cooling rate per unit volume depends upon electron-ion collisions and is also proportional to n_e^2. Therefore, with only photoionization, T_e is nearly independent of n_e. The density dependence of ion ratios has only a minor effect on the equilibrium temperature. However, if an additional heating term is introduced that is proportional to n_e, or did not depend upon density at all, it would dominate the heating in regions with sufficiently low densities, increasing the equilibrium temperature and producing an inverse relationship between T_e and n_e (Reynolds & Cox 1992). This additional heating term would decouple the heating of the gas from its ionization, driving up the the intensities of [S II] and [N II] relative to Hα while not affecting the ionization states of S and N, i.e., allowing the [S II]/[N II] ratio to remain constant. Such heat sources in the WIM may include, for example, photoelectric heating by dust, the dissipation of interstellar turbulence, and coulomb collisions with cosmic rays, which are proportional to n_e (Draine 1978; Minter & Balser 1997; Skibo, Ramaty, & Purcell 1996), and magnetic field reconnection, which may be nearly independent of density (Gonçalves, Jatenco-Pereira, & Opher 1993). Of course, variations in T_e could result from changes in the cooling rate instead of changes in the heating rate. However, temperature excursions from 7000 K to 10,000 K would require a factor of three reduction in the total cooling, and, since N and O are primary coolants, the abundance of oxygen would have to be greatly depleted relative to nitrogen to account for the observed increases in [N II]/Hα. Such abundance variations between the different sight lines seem unlikely, and we therefore conclude that the temperature variations are due to increased heating.

3. THE SUPPLEMENTAL HEATING RATE IN THE MILKY WAY

By assuming that the observed variations in line intensity ratios are produced primarily by variations in electron temperature rather than variations in the ionization parameter, Reynolds et al. (1999) calculated the required heating heating rates in the Milky Way, fitting the predicted variation in [N II]/Hα with temperature to the observed variations in this line ratio. This analysis was carried out for the Perseus spiral arm of the Milky Way, where the associated optical emission lines have been kinematically identified and observed to high Galactic latitude (i.e., high $|z|$) with the WHAM spectrometer (Haffner 1999; Haffner et al. 1999). The temperature was assumed to be set by a balance between the cooling rate per unit volume (Λn_e^2) in the diffuse ionized gas and two heating rates: the net heating by photoionization, given by $G_0 n_e^2$, plus an additional heating term, given either by $G_1 n_e$ or by just a constant G_2. The heating–cooling balance can then be expressed as either

$$\Lambda = G_0 + G_1/n_e, \tag{1}$$

or

$$\Lambda = G_0 + G_2/n_e^2, \tag{2}$$

representing, for example, supplemental heating by photoelectrons from grains (G_1), or by magnetic field reconnection (G_2), respectively. Therefore, depending upon the values of G_1 or G_2 relative to G_0, significantly increased heating (relative to photoionization) can occur as the density decreases. This will result in higher equilibrium temperatures at lower densities. Electron densities vs. $|z|$ in the Perseus arm were obtained from the observed Hα intensities vs. Galactic latitude (Haffner et al. 1999), which then makes it possible to use equations (1) and (2) to calculate various T_e vs. $|z|$ distributions from different combinations of values for G_0, G_1, and G_2 (Reynolds et al. 1999).

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Good fits were obtained to the T_e vs. $|z|$ distribution inferred from the observed increase in [N II]/Hα with $|z|$, demonstrating that a second heat source could in fact account for the observed variations in the line ratios (Reynolds et al. 1999). The best fits were found to have heating rate coefficients given by either

$$G_0 \approx 0.6 \times 10^{-24} \text{ ergs cm}^{+3} \text{ s}^{-1} \ , \tag{3}$$

$$G_1 \approx 1 \times 10^{-25} \text{ ergs s}^{-1} \ , \tag{4}$$

or

$$G_0 \approx 1.2 \times 10^{-24} \text{ ergs cm}^{+3} \text{ s}^{-1} \ , \tag{5}$$

$$G_2 \approx 4 \times 10^{-27} \text{ ergs cm}^{-3} \text{ s}^{-1}. \tag{6}$$

The best fit value for the photoionization heating rate coefficient, $G_0 \approx 1 \times 10^{-24}$ ergs cm^{+3} s^{-1}, corresponds to a stellar ionizing spectrum with $T_{eff} \approx$ 30,000 – 35,000 K (Osterbrock 1989), i.e., late O. This is consistent with the observations of weak He I recombination line emission from the WIM (Tufte 1997; Reynolds & Tufte 1995; Heiles et al. 1996). The values of these coefficients imply that in regions where n_e is greater than 1 cm^{-3}, such as the more traditional H II regions, the heating rate per unit volume is dominated by photoionization, while in regions with densities below 0.1 – 0.04 cm^{-3}, the supplemental heating source dominates, increasing the forbidden line strengths relative to Hα.

This additional heat could be produced by any of a number of interstellar processes. In fact, supplemental heating sources having the required rate of $G_1 n_e \approx 1 \times 10^{-25} n_e$ ergs s^{-1} cm^{-3} have been predicted for the WIM in the Milky Way by models of photoelectric grain heating (Reynolds & Cox 1992; Draine 1978) and by models of the dissipation of interstellar turbulence (Minter & Spangler 1997). For electron temperatures above 8000 K the net heating by standard size grains decreases sharply due to cooling by electron-grain collisions (Draine 1978). Therefore, since the supplemental heating must raise temperatures to 10,000 K or higher, this process cannot be the source unless photoelectric heating in the WIM is dominated by large molecules (e.g., PAHs). Lepp & Dalgarno (1988), for example, concluded that heating by large molecules at a rate near $1 \times 10^{-25} n_e$ ergs s^{-1} cm^{-3} can occur at temperatures up to 18,000 K and "*may be important in heating the intercloud medium and H* II *regions if [large molecules] exist there in sufficient abundances*" (d'Hendecourt & Léger 1987). Minter & Spangler (1997), on the other hand, have also predicted an energy dissipation rate of approximately $1 \times 10^{-25} n_e$ ergs s^{-1} cm^{-3} due to ion-neutral collisional dampening in the Milky Way's nearly fully ionized 10^4 K WIM. They concluded that the dissipation of turbulence probably plays a major role in heating the WIM and contributing to the [S II] and [N II] emission (see also Minter & Balser 1997 and Tufte, Reynolds, & Haffner 1999). Another potential source is coulomb collisions by cosmic ray electrons, which according to some interpretations of the Galactic γ-ray background, could deposit significant power into the interstellar gas (e.g., Skibo et al. 1996; Valinia & Marshall 1998). A heating source that would be nearly independent of density is magnetic field reconnection (Raymond 1992; Birk, Lesch, & Neukirch 1998; Gonçalves et al. 1993). A field strength as high as 7μG (Webber 1998; Heiles 1995) and a time scale of 10^8 yr for the amplification of the field by the Galactic dynamo (Raymond 1992, and references therein) would provide an average power of 6×10^{-28} erg cm^{-3} s^{-1}, a rate that is a factor of about 7 below the value for G_2 given in equation (6) above. However, this is approximately the rate that is needed, if reconnection occurred only within the more limited volume of the WIM, which has a filling fraction of about 0.2.

4. SUPPLEMENTAL HEATING IN NGC 891

The increase in temperature needed to explain the emission line variations in the Milky Way would also account for the observations of NGC 891. A temperature near 7000 K at the midplane rising to 10,000 K at $|z| = 2000$ pc would produce the factor of three increase in [N II]/Hα and [S II]/Hα observed by Rand (1998). Furthermore, such a temperature rise would produce an increase in the [O III] λ5007/Hβ ratio, while keeping [S II]/[N II] constant, as observed, but not explained by the pure photoionization models. If the abundance of O^{++} remained constant with $|z|$, the predicted increase in [O III]/Hβ due to a 3000 K rise in temperature between the midplane and 2000 pc is a factor of 3.6 (Osterbrock 1989). The observed increase is a factor of about 2.5, suggesting that the O^{++} abundance actually decreases slightly at high $|z|$. This temperature rise would therefore eliminate the need for an additional ionization source at higher $|z|$ to explain the observed increase in [O III]/Hβ.

Therefore, like the Milky Way, line ratio variations in NGC 891 that cannot be explained by pure photoionization models could in fact be readily explained by temperature variations produced by a supplemental, non-ionizing heat source. Moreover, the heating rates needed to produce the required temperature changes in NGC 891 are nearly identical to those derived for the Milky Way. The required values for the heating coefficients G_0, G_1, and G_2 can be obtained from equations (1) and (2) by adopting the cooling function given for low density ionized gas in Osterbrock (1989) and by using the electron density distribution given by Rand (1997). While the cooling function in Osterbrock may not be exactly appropriate for the warm ionized medium, for the temperature range considered here ($T_e \geq 7000$ K) it is a good approximation because, like the model H II region in Osterbrock, the cooling function in the WIM is dominated by [O II] and [N II]. This is the same cooling function used for the Milky Way analysis. We find that the required temperature increase from 7000 K to 10,000 K between the midplane and $|z| = 2000$ pc can be produced in NGC 891, if

$$G_0 \approx 0.9 \times 10^{-24} \text{ ergs cm}^{+3} \text{ s}^{-1} \ , \tag{7}$$

$$G_1 \approx 1.1 \times 10^{-25} \text{ ergs s}^{-1} \ , \tag{8}$$

or if

$$G_0 \approx 1.2 \times 10^{-24} \text{ ergs cm}^{+3} \text{ s}^{-1} \ , \tag{9}$$

$$G_2 \approx 5.2 \times 10^{-27} \text{ ergs cm}^{-3} \text{ s}^{-1}. \tag{10}$$

These results are based on the assumption that the filling fraction of the ionized gas in NGC 891 is the same as in the Milky Way, e.g., 0.2 throughout the disk and halo. This results in densities of 0.32 cm^{-3} and 0.058 cm^{-3} within the ionized regions at $|z| = 0$ and 2000 pc, respectively. These rates are virtually identical to those derived for the Perseus arm of the Milky Way (see eqs. 3–6 above; Reynolds et al. 1999), suggesting that similar photoionization and supplemental heating processes exist in both galaxies.

5. TEMPERATURE DIAGNOSTICS

Measurements of higher T_e in regions with higher [N II]/Hα and [S II]/Hα would provide strong, independent support for the existence of a supplemental heating mechanism. These measurements could perhaps be made through accurate observations of the Hα, [N II], and [S II] line widths (e.g., Reynolds 1985), or through observations of other emission lines such as [O II] λ3727 and the extremely faint [N II] λ5755 line, which have higher excitation energies, and thus are more temperature sensitive, than [N II] λ6584 and [S II] λ6716 (see Ferguson et al. 1996). For example, a temperature increase from 7000 K to 10,000 K, which increases [N II] λ6584/Hα and [S II] λ6716/Hα by a factor of three, would also increase the electron temperature diagnostic ratio [N II] λ5755/[N II] λ6584 by a factor of three and [O II] λ3727/Hβ by almost a factor of six. Such observations would provide a clear test of this temperature variation hypothesis.

The recent detection of the [N II] λ5755 emission line in the diffuse interstellar medium does appear to indicate significantly higher electron temperatures in the WIM compared to the brighter, traditional H II regions (Reynolds, Haffner, & Tufte, in preparation). A long integration time spectrum of [N II] λ5755 was obtained, in addition to observations of Hα and [N II] λ6584, toward $\ell = 130.^\circ0$, $b = -7.^\circ5$. A preliminary reduction of the spectra gives [N II] λ6584/H$\alpha \approx 0.4$ and [N II] λ5755/[N II] λ6584 ≈ 0.02 for the velocity integrated emission line profiles in this direction. For comparison, observations of bright, traditional H II regions give [N II] λ6584/H$\alpha \approx 0.2$ and [N II] λ5755/[N II] λ6584 ≈ 0.005. This appears to provide independent evidence that the enhanced [N II] λ6584/Hα ratio toward 130.°0, –7.°5 is the result, at least in part, of a higher electron temperature. Interpreting these line intensity ratios in terms of actual temperatures is complicated by the fact that the [N II] λ5755 and [N II] λ6584 line profiles also indicate significant temperature variations (i.e., variations in the [N II] λ5755/[N II] λ6584 intensity ratio) between the different radial velocity components along this sight line. Thus the mean (velocity integrated) ratios presented above result from a mixture of temperatures, and quantative temperature determinations will require modeling the distribution of temperatures along the line of sight and even perhaps within a single velocity component.

6. SUMMARY AND CONCLUSIONS

The anticorrelation between Hα intensity and the line intensity ratios [N II]/Hα and [S II]/Hα, the large variations in these ratios, the constancy of [N II]/[S II], and even the rise in [O III]/Hβ with increasing [N II]/Hα and [S II]/Hα observed in the diffuse ionized gas of the Milky Way and other galaxies can all be explained if the electron temperature T_e increases with decreasing density n_e. An inverse relationship between T_e and n_e would imply that, in addition to photoionization, which heats at a rate proportional to n_e^2, there is an additional source that is proportional to a lower power of n_e. The existence of such a process would explain a number of observations that cannot be accounted for by pure photoionization models.

Any of a number of processes known to be occurring within the disks and halos of galaxies could be the source of this additional heating. For example, in the Milky Way the dissipation of interstellar turbulence, with a predicted rate $\sim 1 \times 10^{-25} n_e$ ergs cm^{-3} s^{-1} in the WIM (Minter & Spangler 1998), may be the source, raising the possibility that the observed increases in forbidden line intensities (relative to Hα) in galactic halos is the final step in a turbulent energy cascade that begins with large scale motions of the interstellar gas. However, other mechanisms, such as the photoelectric heating by PAHs, magnetic reconnection, or Coulomb interactions with cosmic rays are also possible, provided that within the WIM they have a rate coefficient of the magnitude discussed in Sections 3 and 4 above.

If supplemental heating is actually present in the warm ionized medium of galaxies, diagnostic tools will need to be developed to discriminate between effects due to variations in the ionization parameter and those due to variations in temperature. Additional work certainly needs to be directed toward verifying the existence of supplemental heating—perhaps through accurate measurements of temperatures in regions of enhanced forbidden line emission—and, if verified, finding observational tests to discriminate between the potential supplemental heating mechanisms. This will probably require, in addition to observations of Hα, extensive studies of the Milky Way and other galaxies in the primary cooling lines of [O II] λ3727, [N II] λ6584, and [S II] λ6716, plus the detection and study of much weaker diagnostic lines, such as [N II] λ5755, [O I] λ6300 and He I λ5876, to explore the ionizing radiation field and the temperature and ionization state of the gas.

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