THE EFFECT OF LIGHT SCATTERING BY DUST IN GALACTIC HALOS ON EMISSION-LINE RATIOS

ANDREA FERRARA
Osservatorio Astrofisico di Arcetri, Largo Enrico Fermi 5, I-50125 Firenze, Italy

SIMONE BIANCHI
Dipartimento di Astronomia e Scienza dello Spazio, Università di Firenze, Largo Enrico Fermi 5, I-50125 Firenze, Italy

RALF-JÜRGEN DETTMAR
Astronomisches Institut, Ruhr-Universität Bochum, D-44780 Bochum, Germany

AND

CARLO GIOVANARDI
Osservatorio Astrofisico di Arcetri, Largo Enrico Fermi 5, I-50125 Firenze, Italy

ABSTRACT

We present results from Monte Carlo simulations describing the radiative transfer of Hα line emission, produced both by H II regions in the disk and in the diffuse ionized gas (DIG), through the dust layer of the galaxy NGC 891. This allows us to calculate the amount of light originating in the H II regions of the disk and scattered by dust at high z and compare it with the emission produced by recombinations in the DIG. The cuts of photometric and polarimetric maps along the z-axis show that scattered light from H II regions is still 10% of that of the DIG at $z \sim 600$ pc whereas the degree of linear polarization is small ($<1\%$). The importance of these results for the determination of intrinsic emission-line ratios is emphasized, and the significance and possible implications of dust at high z are discussed.

Subject headings: dust, extinction — ISM: abundances — galaxies: spiral — polarization — radiative transfer — scattering

1. INTRODUCTION

The thick ($z \sim 1$ kpc) *Reynolds layer* of diffuse ionized gas (DIG) that has been discovered in the Milky Way (Reynolds 1990) poses some of the most challenging problems to our understanding of the large-scale structure of the Galactic interstellar medium. Not only its vertical support against the gravitational pull of the Galaxy but also the heating/ionization sources and the excitation conditions are not well understood, and they are matters of current debate. In addition, one would like to understand its possible relationship with the stellar activity in the disk, e.g., H II regions, supernova remnants, and superstructures.

Such ionized layers are also found in several edge-on spiral galaxies, thus lending support to the perception that this structure is not peculiar to the Milky Way. In addition, edge-on galaxies provide a direct way to study the high-z gas since disk and halo separate in projection. The Sbc galaxy NGC 891 is by far the best candidate for this type of study, both because of the huge wealth of data available and for its close similarity to the Milky Way (van der Kruit 1984).

The easiest way to study the DIG is via deep Hα images (Rand, Kulkarni, & Hester 1990; Dettmar 1990); such studies have shown not only the large vertical extension of the gas but also several small-scale structures (asymmetries, filaments, "froth") and a conspicuous number of dust lanes. However, even more relevant to the unsolved problems mentioned above might be the spectroscopic observations of the DIG. Dettmar & Schulz (1992) derived, for the detected emission lines in the range $z = 0$–900 pc, the ratios ([N II] $\lambda 6583$)/H$\alpha \sim 0.32$–1.1 and ([S II] $\lambda 6716$)/H$\alpha \sim 0.11$–0.6. At the midplane, these values are close to the analogous ones observed in H II regions (~ 0.3 and ~ 0.08, respectively), but they depart considerably at higher z. Similar changes have recently been reported for the DIG in NGC 4631 (Golla, Dettmar, & Domgörgen 1996). This evidence suggests the existence of different excitation conditions, possibly due to a change in the spectrum of the radiation field; it also poses a relevant question concerning the amount of light that originates in the disk (where the most obvious ionization sources are located) and light scattered back from dust at high z, which we address in this Letter. In principle, it is also expected that the scattered light is linearly polarized, and thus it is useful to produce synthetic polarization maps as well as photometric maps to be compared with the data. As a by-product, one hopes that this kind of study can have positive feedback on searches for dust in the halo, whose presence has been predicted on several grounds (Ferrara et al. 1991; Ferrara 1993) and has recently been marginally detected by Zaritsky (1994), which could have important cosmological implications.

To answer the above questions, we have performed extensive Monte Carlo computations simulating NGC 891 in detail, which are presented in the next section. The results are discussed in § 3, and conclusions are drawn in § 4.

2. MONTE CARLO SIMULATIONS

We want to follow the radiative transfer of Hα photons, produced both by H II regions in the disk and in the DIG, through the dust layer of the galaxy NGC 891 as a function of height z. To this end, we used a Monte Carlo code simulating dusty spiral galaxies, modeled as bulge-plus-disk systems immersed in a given spatial distribution of dust grains. The extinction parameters (absorption and scattering) of dust

L69

grains are calculated from Mie's theory for a (usually MRN) distribution of grain sizes and materials; the radiative transfer is carried out for the four Stokes parameters, thus enabling us to produce photometric and polarimetric maps of the galaxy once the central optical depth, inclination, and bulge-to-total ratio (i.e., Hubble type) are given. A complete description of the code can be found in Bianchi, Ferrara, & Giovanardi (1996).

To quantify the contribution of Hα photons produced by the H II regions located in the disk versus those truly produced by recombination events in the extraplanar DIG, we have run the code in the following configuration: We model the dust disk according to Kylafis & Bahcall (1987), who concluded that a good representation of the dust distribution has a sech^2 functional form in the vertical direction (we have also tried exponential and Gaussian distributions; see § 3) and is exponential in the horizontal direction (i.e., in the plane of NGC 891) with scale lengths $z_d = 0.22$ kpc and $r_d = 4.9$ kpc, respectively. The central optical depth at $\lambda = 6563$ Å measured along the symmetry axis, also deduced from Kylafis & Bahcall, is $\tau = 0.445$. An inclination $i = 88°5$ is adopted (van der Kruit 1984). Next we specify the distribution of the DIG. This is taken from Dettmar (1990), who concluded that the average Hα distribution (as derived from the emission measure; recall that the electron scale height is twice the scale height of the emission measure) of the DIG in NGC 891 is very well approximated by an exponential distribution with a scale height $z_{DIG} = 0.3$–0.5 kpc; in our simulations, we have used the mean value 0.4 kpc. (Of course, one must keep in mind that this average distribution does not take into account the numerous irregularities observed.) The ionized layer is assumed to be uniform in the radial direction.

Next it is necessary to assume a distribution for the H II regions. Obviously, the true distribution of the H II regions in NGC 891 is not known, because of the heavy obscuration that occurs in the intervening equatorial dust lane. Our strategy has thus been to exploit the fact that NGC 891 is considered to be almost a "twin" of the Milky Way and therefore assume that the radial distribution of H II regions is the same as in the Galaxy, for which extensive literature exists. We rely on the results of Lockman (1990), who presented in his Figure 2 the surface densities of all radio H II regions at Galactocentric radius $\varpi > 1.5$ kpc and Galactic latitude $|l| > 10°$. These results represent the most complete survey of Galactic H II regions, to our knowledge; we assume that, properly scaled, the *shape* of the radial distribution is the same in NGC 891. As for the (vertical) z-distribution of H II regions, although its precise form is not firmly determined, the scale height has been estimated to be $\sigma \sim 70$ pc in the Galaxy (Manchester & Taylor 1981; Reynolds 1989). Dettmar (1990) found for the H II regions in NGC 891 a Gaussian distribution with $\sigma = 170$ pc; we have used this value. However, as long as $\sigma \ll z_{DIG}$, the results are quite insensitive to the precise value of σ.

We are left with the problem of specifying the values of the Hα luminosity of the DIG, Hα(DIG), and of the H II regions, Hα(H II). The total Hα luminosity is given by

$$\text{H}\alpha(\text{tot}) = \text{H}\alpha(\text{H II}) + \text{H}\alpha(\text{DIG}); \qquad (1)$$

we can express the Hα luminosity of the H II regions and of the DIG by means of the *observed* luminosity via the equations

$$\text{H}\alpha^{(0)}(\text{H II}) = p\text{H}\alpha(\text{H II}), \quad \text{H}\alpha^{(0)}(\text{DIG}) = q\text{H}\alpha(\text{DIG}),$$

where $\text{H}\alpha^{(0)}(\text{H II})$ and $\text{H}\alpha^{(0)}(\text{DIG})$ denote Hα photons produced by H II regions and by the DIG, respectively, escaping in the line of sight either directly or after being scattered. We determine p and q from simulations of H II regions or DIG alone immersed in the dust disk by counting the number of photons that have been scattered in the line of sight; from our simulation, we derive $p = 0.54$ and $q = 0.65$.

The final step is to fix the ratio $x \equiv \text{H}\alpha(\text{H II})/\text{H}\alpha(\text{tot})$; this can be done only on a statistical basis. Kennicutt, Edgar, & Hodge (1989) have measured Hα fluxes from the detected H II regions in 30 nearby spirals and Irr galaxies. From their Table 1, corrected for the faint H II regions according to their Table 3, the total average H II luminosity for the 13 Sb–Sc galaxies (encompassing the Hubble type of NGC 891) in the sample comes out to $\langle \text{H}\alpha(\text{H II}) \rangle = 9 \times 10^{40}$ ergs s^{-1}. Since the total Hα luminosity derived by Dettmar (1990) is $\text{H}\alpha(\text{tot}) = 1.4 \times 10^{41}$ ergs s^{-1}, it follows that the best estimate is $x = 0.64$. This value is consistent with the most recent estimates for spiral galaxies: Walterbos & Braun (1994) found $x = 0.6$ for M31; Veilleux, Cecile, & Bland-Hawthorn (1995) estimated $x = 0.7$ for NGC 3079; and, finally, Wyse et al. (1995) obtained $x = 0.47$ and 0.59 for NGC 247 and NGC 7793, respectively. Given the uncertainties associated with this value, we show results for three cases, namely, $x = 0.5$, 0.6, and 0.7, that encompass the experimental limits.

Our simulations calculate the radiative transfer for the H II regions and the DIG in the dust disk separately, and we then co-add the two final images, scaling their intensities appropriately. If N is the number of photons (typically $N = 3 \times 10^7$) for each configuration in the optically transparent case, then we scale by $Nq(1 - x)/x$ the number of photons for the DIG map and by Np the number of photons of the H II regions' map, as can be derived from equation (1) by substituting the above expressions for x, p, and q. The spatial resolution of our final maps is 75 pc pixel^{-1}.

3. RESULTS

In Figures 1 and 2, we show the results for two cuts along the z-axis, the first through the center of the galaxy ($\varpi = 0$), the second at $\varpi = 4.9$ kpc, corresponding to 1 scale length of the dust disk. In each figure we show separately, for three selected values of x, the Hα luminosity profiles of the two components, H II regions and the DIG, the ratio between them, and the linear polarization profile of the Hα for the complete H II–plus–DIG model. The effect of the central hole in the known H II regions' distribution is not relevant in either case since, for $\varpi = 0$, it affects only a region of 50 pc around the center of the image (in the z-direction), as a result of the large inclination of the galaxy, and the cut at $\varpi = 4.9$ kpc (Fig. 2) is well outside the hole. In addition, assuming an exponential or Gaussian vertical distribution of dust with the same scale height does not produce any significant change in the results obtained.

The two figures clearly show that the contribution by scattered Hα(H II) is still 10% of that of the DIG at a height of $z \sim 600$ pc; at these heights, both the profiles and the H II/DIG ratios are rather symmetric because the asymmetries induced by inclined dust disks can be seen only where absorption is high, i.e., near the galactic plane (Bianchi et al. 1996).

The degree of linear polarization is rather small (<1%), mainly because the main source of polarized radiation (Hα photons coming from H II regions and scattered by the extraplanar dust) is highly diluted by the local unpolarized DIG
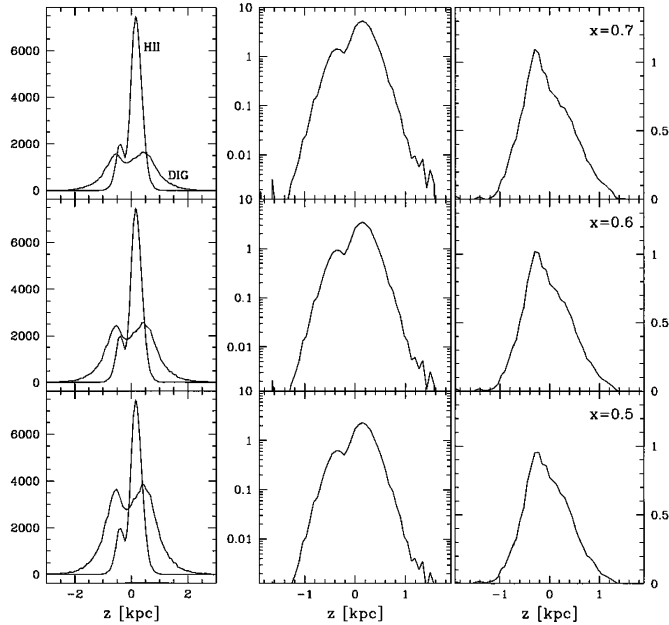
FIG. 1.—Cuts along the z-axis through the center of the galaxy ($\varpi = 0$) for Hα luminosity profiles corresponding to contributions of H II regions and DIG component (*left*), ratio of the two components (*center*), and profiles of the linear polarization degree (*right*). From top to bottom, the plots refer to the cases $x = 0.7$, 0.6, and 0.5, as discussed in § 2.

FIG. 2.—Same as Fig. 1, but for $\varpi = 4.9$ kpc, corresponding to 1 scale length of the dust disk.

emission. The polarization vectors are found to be perpendicular to the plane; this is a known effect for scattering by standard spheroidal dust particles (as can be seen in the similar configurations of emitters and scatterers presented in Bianchi et al. 1996).

4. CONCLUSIONS

The predicted (see Figs. 1 and 2) large contribution of scattered light originating in the plane of NCG 891 to the total intensity of the Hα line emission at considerable height z above the disk can be compared with the observed variations of line ratios with z. As discussed in § 1, emission-line ratios of [N II]/Hα and [S II]/Hα become gradually higher away from the plane. From our results, this gradient can be qualitatively understood as being produced by dilution of the intrinsic DIG ratios by light originating in H II regions and scattered into the line of sight by high-z dust grains.

If we assume that the line ratios at the outermost position ($z \sim 20'' \sim 900$ pc) reported by Dettmar & Schulz (1992) represent the intrinsic line ratios of the DIG, one can obtain a rough estimate at the intermediate position ($z \sim 10''$). From inspection of Figure 2, the contribution of scattered Hα(H II) and Hα(DIG) at this position is close to unity. This results in line ratios of [N II]/Hα ~ 0.7 and [S II]/Hα ~ 0.35, matching the observed values quite well.

The recently reported nondetection of the He I 5876 Å recombination line from the DIG of the Milky Way (Reynolds & Tufte 1995) has raised questions about the predictions of photoionization models and in turn stimulated extensive searches for this critical diagnostic line in extraplanar DIG of external galaxies (Rand 1995). The significant contribution of scattered light predicted by the present work might have an important effect on this measure since, out to $z \sim 600$ pc, part of the He I λ5876 emission might originate in H II regions in the disk.

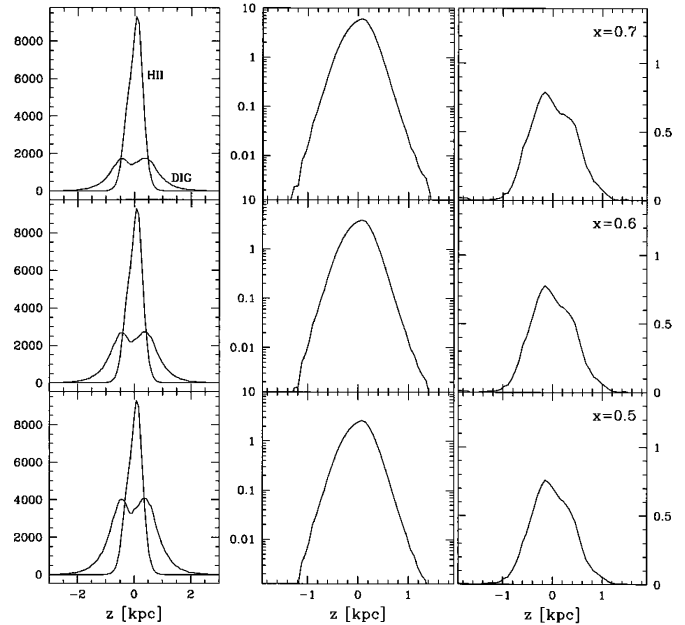The level of linear polarization of the scattered light expected from our models is rather low, typically less than 1%. Therefore it seems currently infeasible to separate the contributions of the H II regions and DIG components from polarization experiments. However, the inclusion of nonspherical grains could increase the polarization degree, although we do not expect a large gain since polarization here is mostly produced by scattering rather than transmission.

One of the assumptions of our model is that the dust distribution has a scale height of 220 pc (Kylafis & Bahcall 1987), much smaller than the DIG one. This would imply that the dust-to-gas ratio must also be a function of z; this is a serious concern for any model addressing the thermal balance of the DIG via photoelectric heating by dust grains (see, e.g., Cox & Reynolds 1992). If, however, in the Reynolds layer the dust-to-gas ratio is similar to that in the plane, this additional dust component could increase the scattered light contribution at high z. Such a low-density dust layer might exist and extend to several kiloparsecs; a viable explanation for its origin is provided by the injection of dust by radiation pressure on grains above powerful OB associations (Ferrara & Shull 1996). Preliminary evidence for such extended dust halos has been already presented by Zaritsky (1994). We have run test cases in which the scale height of the dust is the same as the scale height of the DIG (800 pc), keeping the value of $\tau = 0.445$, implying a dust-to-gas ratio essentially independent of z and equal to that in the plane. The results for the H II/DIG ratios shown in Figures 1 and 2 are increased by a factor of ~ 2. Thus emission-line ratios provide a sensitive tool to investigate the vertical dust distribution.

REFERENCES

Bianchi, S., Ferrara, A., & Giovanardi, C. 1996, ApJ, 465, 127
Cox, D. P., & Reynolds, R. J. 1992, ApJ, 400, L33
Dettmar, R.-J. 1990, A&A, 232, L15
Dettmar, R.-J., & Schulz, H. 1992, A&A, 254, L25
Ferrara, A. 1993, ApJ, 407, 157
Ferrara, A., Ferrini, F., Franco, J., & Barsella, B. 1991, ApJ, 381, 137
Ferrara, A., & Shull, J. M. 1996, in preparation
Golla, G., Dettmar, R.-J., & Domgörgen, H. 1996, A&A, in press
Kennicutt, R. C., Jr., Edgar, B. K., & Hodge, P. W. 1989, ApJ, 337, 761
Kylafis, N. D., & Bahcall, J. N. 1987, ApJ, 317, 637
Lockman, F. J. 1990, in IAU Colloq. 125, Radio Recombination Lines: 25 Years of Investigation, ed. M. A. Gordon & R. L. Sorochenko (Dordrecht: Kluwer), 225
Manchester, R. N., & Taylor, J. H. 1981, AJ, 86, 1953
Rand, R. J. 1995, BAAS, 27, 1354
Rand, R. J., Kulkarni, S. R., & Hester, J. J. 1990, ApJ, 352, L1
Reynolds, R. J. 1989, ApJ, 339, L29
———. 1990, ApJ, 348, 153
Reynolds, R. J., & Tufte, S. L. 1995, ApJ, 439, L17
van der Kruit, P. C. 1984, A&A, 140, 470
Veilleux, S., Cecile, G., & Bland-Hawthorn, J. 1995, ApJ, 445, 152
Walterbos, R. A. M., & Braun, R. 1994, ApJ, 431, 156
Wyse, R. F. G., Ferguson, A. M. N., Gallagher, J. S., & Hunter, D. A. 1995, BAAS, 187, 48.09
Zaritsky, D. 1994, AJ, 108, 1619