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SCATTERING AND DICHROIC EXTINCTION: POLARIMETRIC SIGNATURES OF GALAXIES

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ABSTRACT

Radiation transfer models of the polarization structure of galaxies are presented. These models include dust scattering and dichroic extinction (the mechanism believed to be responsible for producing the observed interstellar polarization within our own Galaxy). As with previous efforts to model galactic polarization maps, the scattering-only models produce a centrosymmetric pattern of the polarization vectors when one is viewing a galaxy pole-on and vectors perpendicular to the galactic plane for highly inclined galaxies. In general, polarization observations of galaxies show vectors that are parallel to the galactic plane or that follow the spiral arm structure, which indicates that the dominant polarization mechanism is from the transmission of light through aligned grains (dichroic extinction). When we include a toroidal magnetic field to align the dust grains and the resulting dichroic polarization in our radiation transfer simulations, we do indeed find that the polarization is parallel to the galactic disk. Depending on the optical depth of the galaxy and the dust properties (albedo, phase function, peak scattering polarization), the polarization patterns at different regions within the galaxy show the signatures of dichroism, scattering, and null points owing to cancellation between the two polarizing mechanisms. We find that in order to reproduce the polarization structure of external galaxies, it is essential to include dichroic extinction in the radiation transfer.

Subject headings: galaxies: ISM — galaxies: magnetic fields — polarization — radiative transfer — scattering

1. INTRODUCTION

Polarization maps of galaxies have been used as probes of galactic dust distributions and also large-scale galactic magnetic fields (see, e.g., Scarrott 1996; Beck & Hoernes 1996; Scarrott, Rolph, & Semple 1990; Wolstencroft et al. 1995; Draper et al. 1995; and references therein). The polarization in the optical and infrared arises through dust scattering of starlight and by dichroic extinction. For dust scattering, the scattered light is polarized perpendicular to the scattering plane, which yields a centrosymmetric pattern of the polarization vectors when viewing a galaxy pole-on and polarization vectors perpendicular to the disk for galaxies viewed at high inclinations (e.g., see models by Bianchi, Ferrara, & Giovanardi 1996; Matsamara & Seki 1989; Jura 1982).

Dichroic extinction is the selective attenuation of different components of the electric vector when light passes through a medium in which the grains are aligned by a magnetic field. When there is a magnetic field present, the grains align with their short axes parallel to the field (see the recent review by Roberge 1996). As light traverses these aligned grains, the component of the electric vector parallel to the long axis of the grains is preferentially absorbed, which gives a net polarization parallel to the magnetic field direction. This mechanism is responsible for the interstellar polarization observed toward many stars in our own Galaxy and has been used to map out the Galactic magnetic field (Mathewson & Ford 1970).

Models of dichroic polarization within our own Galaxy have been presented by Jones (1989) and Jones, Klebe, & Dickey (1992). Their models had a mix of random plus constant components to the magnetic field, which resulted in a polarization level proportional to $\tau^{3/4}$, where τ is the optical depth traversed by the stellar photons. This empirical parameterization comes from correlations between polarization and optical depth for many Galactic sight lines. The polarization is not linear in τ owing to the nonuniformity of the magnetic field direction along any particular photon path. While the analysis of Jones et al. has been successful in modeling Galactic polarizations, the polarization models of external galaxies do not include dichroism (although most do accurately treat multiple scattering off the dust particles) and therefore cannot reproduce the observed polarization patterns. Theoretical models for the polarization produced in external galaxies have primarily focused on the polarization arising from dust scattering (Bianchi et al. 1996; Matsamara & Seki 1989; Jura 1982). However, these models do not resemble most of the polarization maps of galaxies. Most edge-on galaxies exhibit polarization vectors that are parallel to the galactic plane. In face-on spirals, the polarization vectors appear to follow the spiral arms (see, e.g., Scarrott et al. 1990). These patterns have been attributed to dichroic extinction and are indicative of large-scale galactic magnetic fields.

In this Letter, we present Monte Carlo calculations of radiation transfer within galaxies that include both dichroic extinction (using the parameterization of Jones et al.) and multiple dust scattering. The resulting polarization maps compare well with observations, which clearly demonstrates the need to include dichroism in any models attempting to reproduce galactic polarization properties. The following section outlines the galaxy model including the dust and star geometries, the dust optical depth, and the magnetic field structure. Section 3 presents the simulated polarization maps for the cases of scattering only, dichroic extinction only, and the polarization arising from the combination of dichroic extinction and dust scattering. We conclude with some comments on the success of the modeling on reproducing galactic polarization patterns and the potential of this analysis for diagnosing galactic dust and magnetic field structures.

2. GALAXY MODEL

In what follows we adopt a simple picture of a galaxy and neglect density inhomogeneities in either the stars or dust due to clumping or spiral arm structure. We assume that the dust grains are completely aligned in a toroidal magnetic field and that the dichroic polarization increases as $\tau^{3/4}$, as observed locally (Jones 1989).

Our galaxy model consists of two components—stars and dust. Both components are assumed to have a "double-exponential" distribution

$$\rho \propto \exp(-|z|/Z)\exp(-r/R), \qquad (1)$$

where ρ is the star or dust density and Z and R are the star or dust scale lengths in the vertical, z-direction, and in the galactic equator, r-direction, respectively. For the purpose of this initial investigation, we assume that these scale lengths are the same for both stars and dust with $Z = 0.3$ kpc and $R = 4$ kpc. These are typical parameters and were among those adopted by Bianchi et al. (1996) in their models. We further assume that the galaxy has an outer radius of 20 kpc and a vertical extent of 1.5 kpc (i.e., 5 scale lengths in both the r- and z-directions). We have not included any bulge emission that would provide a centrally concentrated source of unpolarized emission (see, e.g., Bianchi et al. 1996). The dust optical depth in the I band along the total z-direction through the center of the galaxy is chosen to be 1.5. At a radius of 8 kpc, this gives a vertical optical depth from the galactic plane of 0.1, which is comparable to that at the Sun's distance in our own Galaxy.

The dust parameters are the phase function for single scattering, asymmetry parameter (g), albedo (a), and peak linear polarization ($P_{\max}$) as described in Wood et al. (1996b) and Whitney & Hartmann (1992, 1993). We model the scattering with the Henyey-Greenstein phase function (Henyey & Greenstein 1941) and choose dust parameters relevant to the I band, namely $g = 0.3$, $a = 0.6$, and $P_{\max} = 0.7$. These parameters are based on White's (1979) analysis for a Mathis, Rumpl, & Nordsieck (1977) dust mixture. This parameterization of the dust scattering does not account for differences in the phase function and the resulting polarization for scattering off nonspherical aligned grains. The dust grains are assumed to be completely aligned by a toroidal magnetic field everywhere in the galaxy. Thus, the magnetic field at each point in the galaxy is perpendicular to the cylindrical radius vector, and the field strength does not enter the calculation (Jones et al. 1992).

The radiation transfer is performed using the Monte Carlo radiation transfer code described in Wood et al. (1996a). This code follows photon packets to random interaction locations where, depending on the albedo, they are either absorbed or scattered into new directions and become partially polarized. Observationally, Jones (1989) and Jones et al. (1992) found that the dichroic polarization within our own Galaxy at K could be approximated by $P_K(\%) = 2.23\tau_K^{3/4}$. We approximate the I-band dichroic polarization in a similar manner, following Jones (1989) and using the interstellar polarization law (Wilking, Lebofsky, & Rieke 1982) yields $P_I(\%) = 2.5\tau_I^{3/4}$. To include the polarizing effects of dichroic extinction, at each interaction point we polarize the photon packet by $P_I \sin^2 \zeta$ in a direction parallel to the local magnetic field, where ζ is the angle between the photon direction and the magnetic field direction at the interaction location. The dichroism has thus been included using the parameterization of Jones et al. (1992). This approach differs from a more detailed treatment that would account for the magnetic field orientation, grain alignment, and the differences in the absorption cross sections along orthogonal grain axes (which in turn depend on the

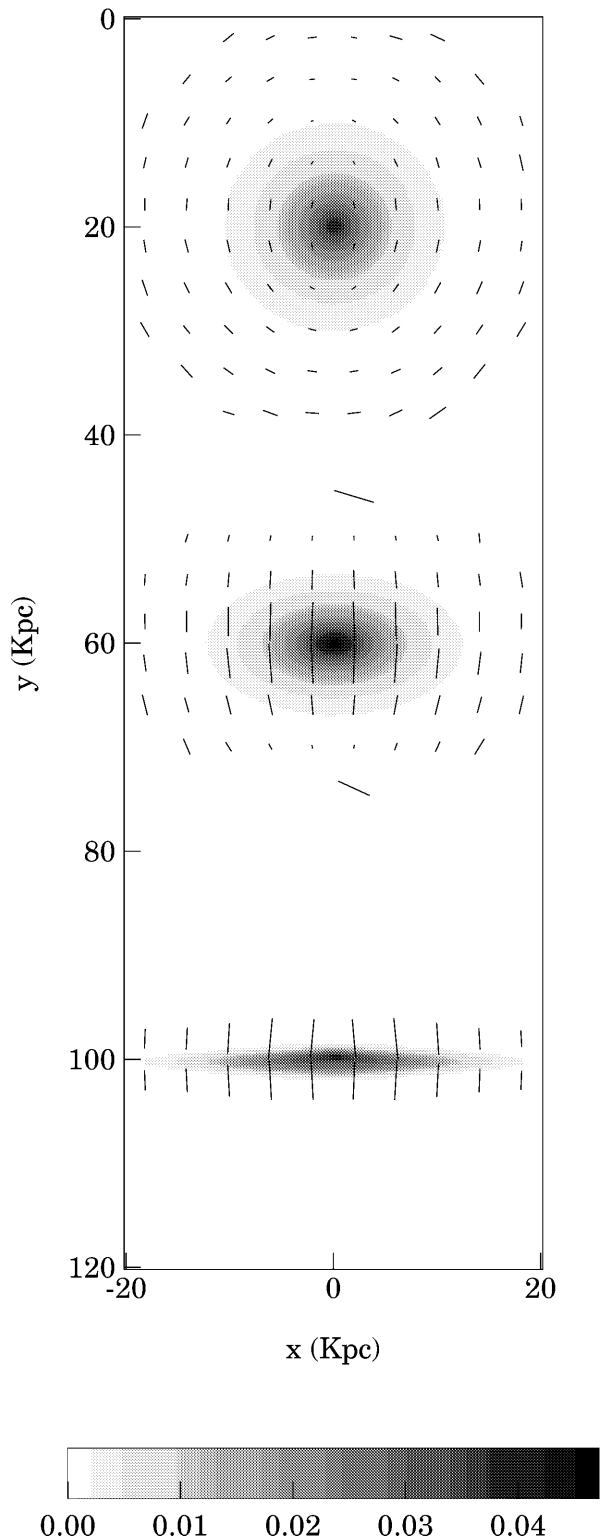

FIG. 1.—Polarization and flux maps for the galaxy with scattering only. The maximum polarization in this figure is 2%. The three images are for inclinations of 18° (*top*), 60° (*center*), and 87° (*bottom*). Note that since the scattered radiation is polarized perpendicular to the scattering plane, the polarization vectors form a centrosymmetric pattern for pole-on viewing and are perpendicular to the galactic disk at higher inclinations.

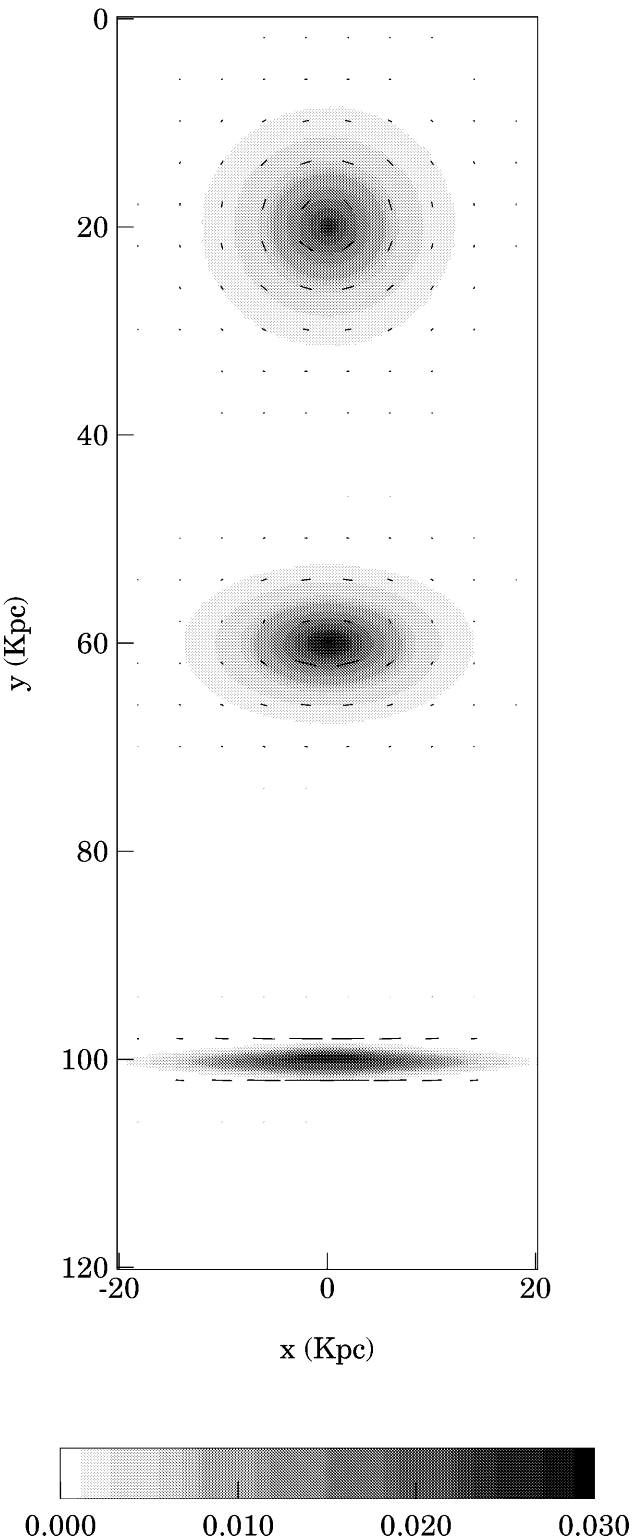

FIG. 2.—Polarization and flux maps for the galaxy with no scattering (a = 0). The maximum polarization in this figure is 2%. In this case, the polarization is due to dichroic extinction only, and the polarization vectors are parallel to the toroidal magnetic field, yielding the centrosymmetric pattern at low inclinations and vectors parallel to the galactic disk for edge-on viewing.

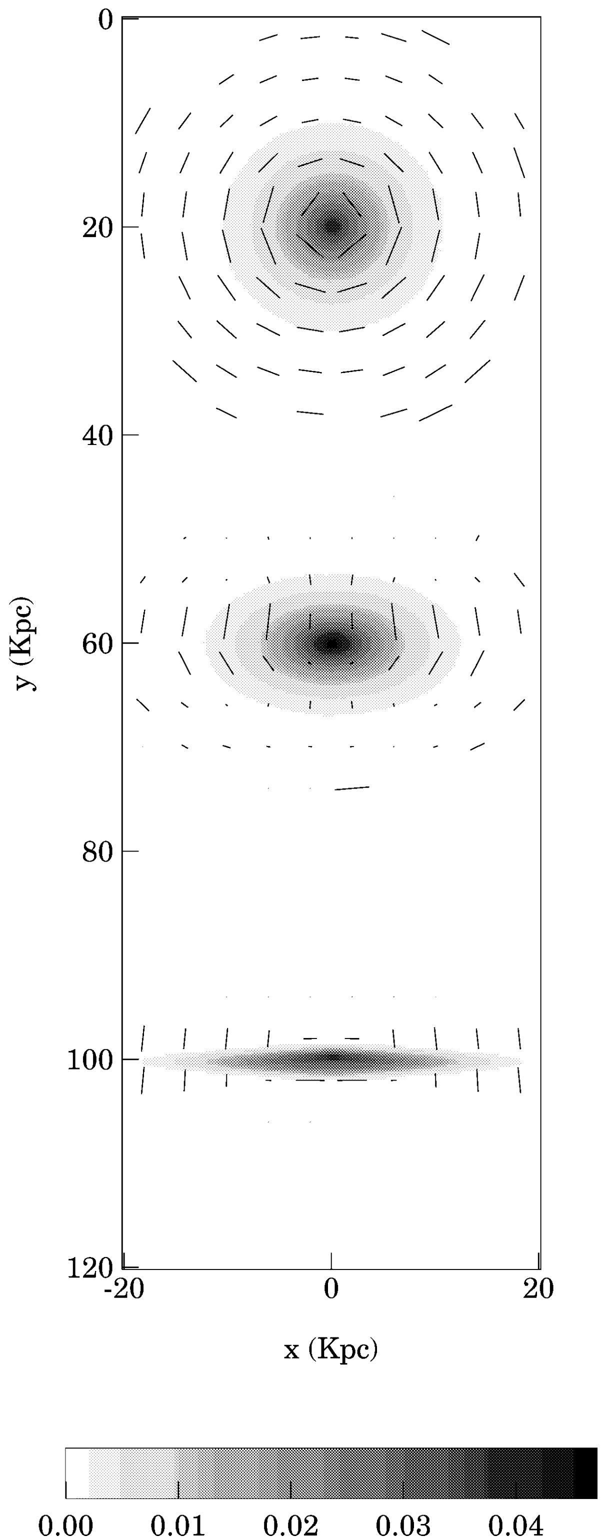

FIG. 3.—Polarization and flux maps for the galaxy with both scattering and dichroic absorption included in the radiation transfer. The maximum polarization in this figure is 1%. Note that for low inclinations, the polarization pattern is centrosymmetric as in the upper images in Figs. 1 and 2. For higher inclinations, we see the competing effect of the different polarizing mechanisms—vectors parallel to the galactic disk at the center of the images, where dichroism is dominant, and perpendicular to the disk in the outer regions, where scattering dominates the polarization.

polarization of the incident radiation field). We feel that using the parameterization of Jones et al. of the dichroism is sufficient for a first approach to the problem.

3. RESULTS

Figures 1, 2, and 3 show the simulated polarization maps for our model galaxy viewed at inclination angles of 18°, 60°, and 87°. Figure 1 shows the case of scattering only, Figure 2 shows the case when there is only dichroism and no scattering ($a = 0$), and Figure 3 presents the polarization maps including both scattering and dichroism.

For the scattering-only case (Fig. 1), the polarization vectors form a centrosymmetric pattern for low inclinations and are perpendicular to the galactic plane for high inclinations. These patterns arise because the scattered radiation is polarized perpendicular to the scattering plane (Bianchi et al. 1996; Matsamara & Seki 1989; Jura 1982). In Figure 2, there is no scattering ($a = 0$), and the polarization is due entirely to the dichroic extinction. In this case, the polarization vectors are parallel to the magnetic field direction at the point at which the photons exit the galaxy. With our choice of a toroidal magnetic field, this yields a centrosymmetric pattern for low inclinations similar to the scattering-only case. However, at high inclinations, the polarization vectors are parallel to the galactic disk, as expected for the chosen magnetic field.

Figure 3 shows the polarization maps for the case in which both scattering and dichroic extinction are included in the radiation transfer calculation. For the pole-on case, the polarization vectors follow the centrosymmetric pattern common to both Figures 1 and 2. However, for higher inclinations, we see the signatures of both polarization mechanisms at different regions in the galaxy. Near the center of the images, the scattering polarization is small since the radiation field becomes quite isotropic. In these regions, the dichroism dominates, which yields polarization vectors parallel to the galactic disk. Scattering dominates the polarization in the outer regions, where the radiation field is highly anisotropic. In this particular simulation, a scattered photon may be up to 70% polarized, whereas dichroism adds on the order of a few percent polarization per optical depth. Thus, in the outer regions, the polarization pattern shows the signature of scattering with the vectors being perpendicular to the galactic plane. At some intermediate location, the scattering and dichroic polarization will cancel, yielding the so-called null points observed in galactic polarization observations (see, e.g., Draper et al. 1995).

4. DISCUSSION

When both scattering and dichroism are included in radiation transfer models, we have a natural explanation for the observed polarization patterns in highly inclined galaxies. In the inner regions, where dichroism dominates, the polarization is parallel to the galactic plane. This polarization level decreases with increasing radius owing to polarimetric cancellation by scattering. At some point, the scattering and dichroic contributions exactly cancel, yielding a polarization "null point." Beyond the null point, in the scattering-dominated regions, the polarization increases and is perpendicular to the galactic plane. The details of this polarimetric behavior are dependent on the optical depth of the galaxy and the dust albedo and maximum scattered polarization. Thus, the polarization null points and the orientation of the polarization vectors will be a function of wavelength.

In the optical polarimetric maps of NGC 4565 (Scarrott et al. 1990), we see evidence for this progression from dichroic polarization at the center, through the null points, and then increasing scattering polarization in the outer regions. Similar patterns at optical wavelengths are observed in other galaxies (see, e.g., Scarrott et al. 1990; Draper et al. 1995). At infrared wavelengths (H and K bands), T. J. Jones (1996, private communication) also observes that the polarization of NGC 4565 is parallel to the galactic plane throughout the dust lane.

The model polarization maps presented in this Letter have been calculated for only one wavelength, dust optical depth, and a very idealized star-plus-dust geometry. In addition, we have included the dichroic polarization in an approximate manner, based on empirical relations between interstellar polarization and optical depth for our own Galaxy. A more detailed treatment of the dust scattering should include the differences in scattering cross sections along different grain axes, which would thereby include interstellar polarization explicitly rather than with the empirical relation that we have adopted. However, this representative model set quite successfully reproduces the general characteristics of galactic polarization maps. It also indicates that it is imperative to include dichroic extinction in any models that attempt to reproduce polarization patterns in external galaxies. Although many authors have proposed that the observed polarization patterns are the result of dichroic extinction, until now this effect had not been included in radiation transfer codes. Combining dichroic extinction and multiple scattering, as we have done, with more complex models of the galactic emission and dust density structures (bulges, spiral arms, etc.) will provide probes of dust optical depths and magnetic field structures through detailed multiwavelength modeling of the polarization patterns and null points.

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