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MODELING POLARIZATION MAPS OF EXTERNAL GALAXIES

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ABSTRACT

We extend previous radiation transfer models of disk galaxies to include bulge plus disk systems. The Monte Carlo radiation transfer models include the polarizing effects of dust scattering and transmission through aligned grains. We assume that the dust grains are aligned by large scale toroidal magnetic fields and we model the interstellar polarization using empirical formulae derived for the Milky Way. Although our galaxy models do not include dust or star inhomogeneities arising from clumping or spiral arm structures, they do successfully reproduce the observed dust lanes and polarization patterns and null points. We apply our techniques to NGC 4565 and NGC 891 which are examples of nearly edge-on spiral galaxies with prominent dust lanes. We can successfully model the polarimetric structure of NGC 4565 with uniformly aligned grains and a smooth dust lane. However, our models fail to reproduce the structure within NGC 891's dust lane. This failure is attributed to the striking disk activity present in NGC 891 and the polarimetric evidence for vertical magnetic field structures. The dust lane activity and non-toroidal magnetic fields in NGC 891 appear to break the large scale grain alignment to such an extent that our smooth model is unable to reproduce the flux and polarization maps. Although NGC 891 is often assumed to be very similar to our own Galaxy, our modeling suggests that, polarimetrically at least, NGC 4565 behaves more like the Milky Way than does NGC 891. © *1997 American Astronomical Society.*
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1. INTRODUCTION

Optical and near-IR polarization maps of galaxies exhibit polarization patterns indicative of the combination of dust scattering and dichroic extinction (e.g., Jones 1997; Scarrott 1996; Scarrott *et al.* 1990; Wolstencroft *et al.* 1995; Draper *et al.* 1995). Depending on the wavelength, light scattered by dust may be highly polarized with the polarization direction perpendicular to the scattering plane (40% at V and 85% at H for 90° scattering; White 1979). Scattering alone yields a centrosymmetric pattern of polarization vectors for face-on viewing and vectors perpendicular to the galaxy for higher inclinations (see models by Bianchi *et al.* 1996; Matsamara & Seki 1989; Jura 1982). Dichroic extinction arises from the selective attenuation of starlight as it passes through a region of aligned grains. The extinction cross section is larger along the grain's long axis so that the transmitted light becomes polarized parallel to the grain's short axis, with typical values of a few percent per optical depth at K (Jones 1989a; Jones *et al.* 1992). Interstellar magnetic fields determine the alignment of grains with their short axes parallel to the magnetic field direction (see recent reviews by Roberge 1996; Jones 1996)—thus dichroic polarization is parallel to the projection of the magnetic field direction on the plane of the sky.

In external galaxies, the polarization vectors are observed to follow the spiral arms in face-on spirals and are parallel to the dust lanes for highly inclined galaxies (e.g., Scarrott 1996; Scarrott *et al.* 1990). These polarization patterns are attributed to dichroic extinction and are cited as evidence for large scale toroidal galactic magnetic fields (Scarrott *et al.* 1990). For highly inclined galaxies with toroidal magnetic fields, the directions of scattering and dichroic polarization are perpendicular, thus in different regions either scattering or dichroism dominates the polarization structure, and where the two components cancel we see polarization null points (Scarrott *et al.* 1990; Draper *et al.* 1995).

Radiation transfer models of external galaxies that include absorption and scattering by dust have been successful in reproducing the observed flux images and have been used to determine the dust and stellar scalelengths (e.g., Kylafis & Bahcall 1987). To date, most polarization models have only included the polarization arising from dust scattering and so were unable to reproduce the observed polarization structures and null points (Bianchi *et al.* 1996; Matsamara & Seki 1989; Jura 1982). In a preliminary investigation, Wood (1997) presented Monte Carlo models of galactic polarization maps that included dust scattering plus interstellar polarization using an empirical optical depth law observed in the Milky Way. Using this combination of scattering plus dichroism, Wood's model calculations reproduced the correct qualitative behavior for polarization structures in exter-

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nal galaxies—polarization vectors parallel to the dust lanes for edge-on galaxies where dichroism dominates, polarization null points due to cancellation from scattering, and polarization vectors perpendicular to the galactic plane in regions where scattering dominates the polarization. In that paper only disk galaxies were investigated.

We now extend our models to include bulge emission and apply our modeling techniques to polarization maps of two almost edge-on galaxies with dust lanes—NGC 4565 and NGC 891. We find that the polarimetric structure of NGC 4565 can be reproduced with our model, whereas that of NGC 891 cannot. Since we have used the Milky Way's interstellar polarization and optical depth correlation, this leads us to the conclusion that NGC 4565 behaves more like the Milky Way, with large scale magnetic fields aligning the dust grains. For NGC 891, our smooth model combined with the empirical interstellar polarization law is clearly inadequate for this system which exhibits a turbulent dust lane and other evidence for vertical magnetic field structures which disrupt the large scale dust grain alignment. First of all we present the details of our model.

2. MODEL DETAILS

In this section we outline the details of our model including the galaxy geometry and luminosity; galactic magnetic field structure; dust geometry, scattering, and extinction properties; interstellar polarization, and the Monte Carlo radiation transfer techniques employed.

2.1 Galaxy Parameters

As in Wood (1997) our galaxy model consists of two components—stars and dust distributed with "double-exponential" distributions

$$\rho \propto \exp(-|z|/Z)\exp(-\varpi/R), \quad (1)$$

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, ϖ direction, respectively. Other investigations have used sech and sech^2 for the z distribution of stars and dust (e.g., Van der Kruit & Searle 1981; Kylafis & Bahcall 1987; Bianchi *et al.* 1996; Rice *et al.* 1996). Since the differences in the success of the fits to the z distribution are small between the various functions, we use the double exponential distribution of Eq. (1) in our simulations. In addition to the luminosity of the galactic disk, we now include emission from a spherical bulge. The bulge luminosity is chosen to follow the Jaffe (1983) distribution as used by Bianchi *et al.* (1996),

$$\rho_b \propto \frac{1}{(r/r_b)^2[1+r/r_b]^2}, \quad (2)$$

where r is the distance from the galactic center and r_b is the bulge scale radius. We must further specify the bulge and disk luminosities (B/T ratio) so that we may determine the number of photon energy packets to be released in the Monte Carlo radiation transfer simulation (see below). We also impose an outer cut-off, $r_{\rm cut}$, for the release of bulge photons. Different galaxy types may be simulated by varying the luminosities of the bulge and disk.

Throughout this paper we assume a toroidal galactic magnetic field geometry, so that the magnetic field direction at any position within the galaxy is in the plane and perpendicular to a cylindrical radius vector. This geometry is adopted based on dichroic polarization observations within the Milky Way and external galaxies. In our own Galaxy, the large scale magnetic field geometry is predominantly confined to the Galactic plane, with the exception of large loops as a result of supernovae in the Scorpius and Ophiucus regions, and other local departures within the Taurus, Perseus, and Orion star forming regions (Zweibel & Heiles 1997). Such detailed magnetic structures cannot in general be traced in the lower resolution polarization maps of external galaxies, with only large scale magnetic field structures discernible. In galaxies with relatively undisturbed dust lanes, large scale magnetic fields also appear to be confined to the galactic plane (Scarrott *et al.* 1990).

Note that our galaxy model consists of smooth dust and stellar components, and that we do not include inhomogeneities arising from clumping or spiral arm structure. Monte Carlo radiation transfer investigations of galaxies with clumpy dust distributions have been conducted by Witt & Gordon (1996). For galaxies viewed at high inclinations, they find that the clumpy and smooth models are very similar since both clumpy and smooth distributions of dust yield optically thick dust lanes. For galaxies viewed at low inclination, which do not concern us here, they find that dust clumping allows for the escape of photons from the optically thinner "interclump regions," thereby raising the observed surface brightness compared to smooth models (see also Boisse 1990). At each wavelength, we use the same bulge to total luminosity ratio, adopt only one radial and one vertical scalelength for the stellar distribution, and do not account for the spatial variation in luminosity from different stellar populations at different scaleheights above the plane. Therefore the predicted galaxy color is likely to be in error. The level of modeling adopted for this investigation is justified because we are primarily interested in explaining the large scale polarimetric characteristics of external galaxies and are not concerned with the observed small scale flux features.

2.2 Dust Extinction and Scattering Parameters

The dust extinction law is assumed to be the same as that for the Milky Way (note that extinction refers to both scattering and absorption), so that the optical depth in the galaxy at H is one fifth that at V (e.g., Cardelli *et al.* 1989). The galaxy optical depths are parameterized in terms of the vertical optical depth, $\tau_{\rm pole}$, measured vertically from the midplane through the center of the galaxy. From Eq. (1), the optical depth in the equator from the center of the galaxy is then, $\tau_{\rm eq}=R_{\rm dust}/z_{\rm dust}\tau_{\rm pole}$.

We use the Henyey-Greenstein phase function to represent the dust scattering (Henyey & Greenstein 1941), with the albedo, a, asymmetry parameter, g, and polarization per scattering, p, taken from White's (1979) calculations for a Mathis *et al.* (1977) dust mixture. The relevant parameters for the V and H bands are presented in Table 1. Observa-

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TABLE 1. Dust parameters.

	τ	a	g	p
V	1	0.5	0.44	0.4
H	0.2	0.3	0.06	0.85

tionally, there is a large spread in the values for a and g. The albedo has been measured to lie between 0.4 and 0.8 in the UV and remains relatively constant at about 0.6 in the optical, while the asymmetry parameter has been measured to lie between 0.4 and 0.8 from the UV through optical, with large errors on these values (K. Gordon, private communication). (Note that for completely forward scattering $g=1$ and for isotropic scattering $g=0$.) With the large observational uncertainties, we choose to keep the dust properties from Table 1 constant for all our models.

2.3 Interstellar Polarization

Jones (1989a,b) found that the polarization at K showed a clear trend with optical depth, but this trend was not linear. He found that the polarization was roughly proportional to $\tau_K^{3/4}$ over a wide range in optical depth. This trend in interstellar polarization was subsequently modeled by Jones *et al.* (1992) with a model that envoked a 50/50 mix of constant and random components to the interstellar magnetic field. The random component decorrelated over an optical depth of about 0.1 at K and was responsible for the departure from a linear trend of polarization with optical depth. Rather than incorporate this complicated a description of interstellar polarization into our Monte Carlo model, we will simply adopt the empirical fit given in Jones (1989a,b).

In our Monte Carlo radiation transfer, we include interstellar polarization by polarizing the photon packets in a direction parallel to the local magnetic field direction (see next section). A more precise calculation would include aligned grains, the extinction cross sections along different grain axes, the polarization of the incident radiation field, etc. However, grain shapes are not known (infinite cylinders are a relic of previous analytic models); the grain alignment mechanism and degree of alignment are uncertain; cross sections are calculable for non-spherical grains (e.g., Wolff *et al.* 1996), but interstellar grains are believed to be spinning, so this makes for a more complex calculation. With all these complications and uncertainties, we have chosen to use the empirical K band polarization–optical depth relation observed for the Milky Way. We then scale this K band formula to the V and H bands using the relations between P_K and τ_K, the Milky Way wavelength dependence for the optical depth scaling, and the Serkowski wavelength dependence for interstellar polarization, as follows.

For the K band, Jones (1989a,b) found that $P_K/\tau_K=2.2\%$. Using the Galactic interstellar extinction law (Cardelli *et al.* 1989), we find that $\tau_V/\tau_K\approx 10$ and $\tau_H/\tau_K\approx 2$. The Serkowski law for the interstellar polarization is

$$P_\lambda = P_V \exp(-0.935[\ln \lambda_V/\lambda]^2). \tag{3}$$

This then yields $P_V/P_K\approx 6$ and $P_H/P_K\approx 2$. Combining this information then yields

$$\frac{P_V}{\tau_V}=\frac{P_V}{P_K}\frac{\tau_K}{\tau_V}\frac{P_K}{\tau_K}\approx 1.3, \quad \frac{P_H}{\tau_H}=\frac{P_H}{P_K}\frac{\tau_K}{\tau_H}\frac{P_K}{\tau_K}\approx 2.2. \tag{4}$$

Assuming that the $\tau^{3/4}$ relation holds over the wavelength range we are investigating we then obtain, $P_V(\%)=1.3\tau_V^{3/4}$ and $P_H(\%)=2.2\tau_H^{3/4}$.

2.4 Radiation Transfer

The Monte Carlo radiation transfer code (Wood *et al.* 1996) follows photon packets to random interaction locations where they are either absorbed or scattered into new directions becoming partially polarized. The photons and their polarization are tracked until they are either absorbed or escape from the galaxy which is assumed to extend to five scalelengths in the vertical and horizontal directions. Upon exiting the galaxy, the photons are placed into direction of observation bins and projected onto a plane to create the two dimensional images presented below. To include the polarizing effects of dichroic extinction, at each interaction point we polarize the photon packet by $P_\lambda \sin^2\zeta$ 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. As discussed above, this empirical treatment of the interstellar polarization comes from scaling relations observed for the Milky Way, so in effect our modeling scheme will determine whether other galaxies behave polarimetrically like our own Galaxy.

3. OPTICAL AND IR DATA

The two galaxies to which we apply our modeling techniques are NGC 4565 and NGC 891, which are nearly edge-on galaxies with strong dust lanes. Van der Kruit (1984) presented an analysis of these galaxies and compared them with the Milky Way, finding that the stellar scalelengths are very similar in all three. Our modeling is motivated by the new near-IR imaging polarimetry of NGC 4565 and NGC 891 (Jones 1997) and the failure of previous polarization models to satisfactorily reproduce galactic polarization structures. The optical polarimetry data, to which we will compare our models was presented by Scarrott *et al.* (1990) for NGC 4565 and Scarrott & Draper (1996) and Fendt *et al.* (1996) for NGC 891. In addition to the optical and near-IR polarimetry data, Howk & Savage (1997) recently obtained high angular resolution optical images from the WIYN 3.5 m telescope. These images were taken as part of a project to probe the distribution of dust and gas at high latitudes in external galaxies. They find that the dust lane of NGC 891 displays a far greater level of activity and filamentary structures than that of NGC 4565. We shall return to this point in our discussion of the two galaxies.

3.1 NGC 4565

NGC 4565 has been extensively studied in the optical (Van der Kruit & Searle 1981), IR (Rice *et al.* 1996), and in H I (Rupen 1991). This nearly edge-on Sb galaxy extends over 16′, has a visual magnitude of $m_V=10.3$, and is at a distance of 10 Mpc (Sandage & Tammann 1976). From

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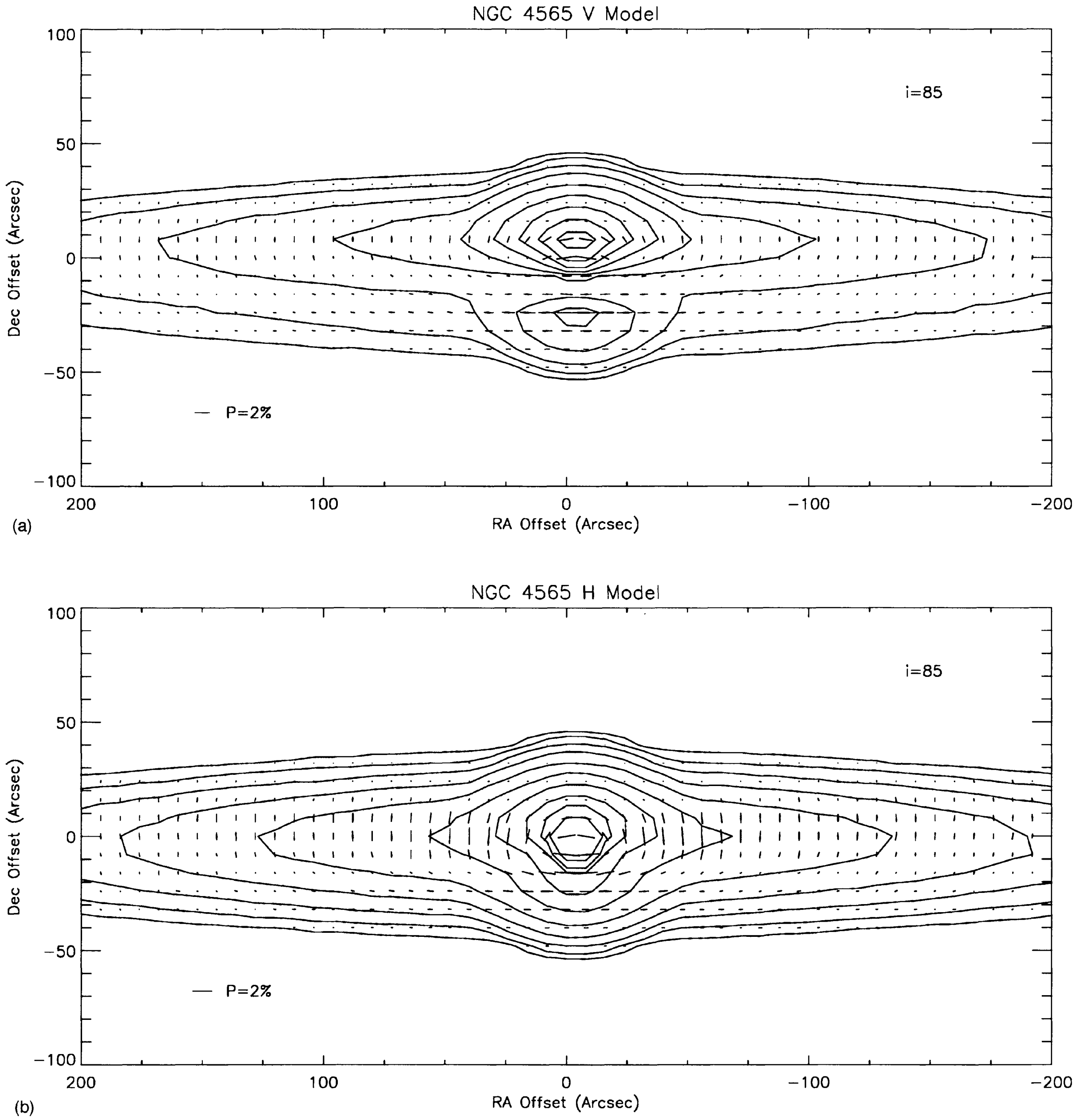

FIG. 1. (a) *V* band model of NGC 4565. The contour levels are at half-magnitude spacing. Note the strong dust lane, polarization parallel to the dust lane in the inner regions, the null points around ±100″, and the vertical, dust scattered polarization outside the dust lane. (b) *H* band model of NGC 4565. Note the weaker dust lane compared to the *V* band model and that the polarization null points occur at a smaller radius due to the higher level of the dust scattered polarization.

analysis of optical photometry, Van der Kruit (1984) derived that the stellar scalelengths were $R_\star = 5.5$ kpc and $z_\star = 0.79$ kpc, where the stellar density was modeled as being exponential in ϖ and sech^2 in z. We use the same $R_\star$ and a slightly smaller value of $z_\star = 0.4$ kpc for the exponential z distribution in our simulations.

The optical (Scarrott *et al.* 1990) and *H* band (Jones 1997) polarization maps of NGC 4565 both show polarization vectors parallel to the dust lane. This polarization pattern is attributed to dichroic extinction through grains aligned by magnetic fields that are coherent over kiloparsec sizescales. The *H* band image maps the polarization structure within a 40″ radius of the galactic center, and does not show the polarization null points that occur in the optical image in the dust lane near a radius of 100″. Beyond this radius and outside of the dust lane, the optical map shows polarization vectors that are perpendicular to the galactic disk, indicating polarization arising from dust scattering.

Figures 1(a) and 1(b) show our *V* and *H* band model images for NGC 4565. The contour levels are at half magnitude intervals and the polarization scale is shown on the figures. The model shown in Fig. 1(a) was obtained with stellar

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TABLE 2. Galaxy model parameters.[a]

	$R_\star$	$Z_\star$	$R_{\rm dust}$	$z_{\rm dust}$	R_b	$r_{\rm cut}$	B/T	$\tau_{\rm pole}(V)$	$\tau_{\rm eq}(V)$
NGC 4565	5.5	0.4	5.5	0.25	1	2.5	0.4	1	22
NGC 891	4.9	0.93	4.9	0.22	1	2.5	0.1	1	22.3

[a]All scalelengths are in kpc.

scalelengths of $R_\star=5.5$ kpc (Van der Kruit 1984) and $Z_\star=0.4$ kpc. Our models appear to best match the optical data of Scarrott *et al.* (1990) with dust scalelengths of $R_{\rm dust}=5.5$ kpc, $Z_{\rm dust}=0.25$ kpc; bulge radii of $r_b=1.0$ kpc and $r_{\rm cut}=2.5$ kpc; a bulge to total luminosity ratio of 0.4; V band vertical optical depth of $\tau_{\rm pole}=1$ (see Table 2). The same stellar and dust scalelengths were used for the H band model, but the dust properties were altered to reflect the lower opacity and different scattering parameters as in Table 1. Note that we have not attempted to perform a detailed parameter fit to the data, but have taken values for the radial stellar distribution from previous studies and our vertical (exponential) scaleheight is similar to that found with sech and sech^2 distributions. Since the goal of this paper is to model galactic polarization structures, we are content with our fit to the large scale characteristics of the flux image and focus our attention on the resulting polarization structure.

With these caveats regarding the limitations of our model, we note that it does reproduce the overall flux contours and fits the polarization structure rather well. In particular, the optical model predicts the polarization null points within the dust lane close to their observed locations of $\pm 100''$. Outside the dust lane, the model shows polarization vectors that are perpendicular to the galactic disk and very low polarizations in the upper half of the bulge. In the lower half of the bulge, the model predicts that the polarization remains parallel to the dust lane, whereas in both the optical and IR images the polarization in this region departs from being parallel to the dust lane. This discrepancy most likely arises through our assumption of a toroidal magnetic field *everywhere* within the galaxy. Wherever dichroism dominates the polarization, as it does within the dust lane and in transmission of radiation from the lower half of the bulge through the galactic disk, our model will yield a polarization pattern parallel to the galactic plane. Clearly this is an extremely idealized magnetic field geometry and the observed polarization patterns in the optical and IR indicate that in localized regions there are departures from a purely disk field.

The H band model image (Fig. 1(b)), shows a much weaker dust lane, as is to be expected from the lower optical depth in the IR. The polarization structure displays the same overall characteristics as the optical model, with vectors parallel to the galactic plane within the dust lane and scattering polarization at large radii and outside the dust lane. Within the dust lane, our model shows a good match to the H band polarization pattern (Jones 1997). However, on either side of the bulge the model predicts a scattering polarization pattern that is not present in the data at the level predicted by the model. This may be due to uncertainties in the adopted dust scattering parameters (Table 1). We note that our model predicts that the turnover from dichroic to scattering polarization occurs at a smaller radius in the IR than in the optical. This arises because of the cancellation between scattering and dichroism, which produce orthogonal polarization patterns for the adopted toroidal magnetic field geometry. The dichroic polarization is larger per τ in the IR than in the optical (2% compared to 1.4%); however, the polarization per scattering is also much larger (85% compared to 40%). Even though the optical depth and albedo are smaller in the IR simulation (therefore there is less scattering), the larger scattering polarization is the dominant effect, cancelling the dichroic polarization yielding smaller dust lane polarizations and null points at smaller radii at H than at V. Further IR imaging polarimetry of the outer regions of NGC 4565 (and other galaxies) would test this model prediction.

From the success of our polarimetric modeling, we are able to draw similarities between NGC 4565 and our own Galaxy. The interstellar polarization in our model has been included using observed trends between polarization and optical depth within the Milky Way. That this relation is able to reproduce the polarization within NGC 4565 suggests that its magnetic field structure is similar to that in the Milky Way. Although it is a crude representation, our adoption of a toroidal component to the magnetic field that is coherent throughout the galaxy appears consistent with the observations. In contrast, we now investigate a galaxy in which the smooth field geometry of our models is clearly a poor approximation.

3.2 NGC 891

It has been proposed that, like NGC 4565, the edge-on galaxy NGC 891 is morphologically very similar to our own Galaxy (Vand der Kruit 1984). As is the case with NGC 4565, its large angular size and strong dust lane have made it a popular target of observation. Kylafis & Bahcall (1987) modeled NGC 891 as an edge-on galaxy with stellar and dust scalelengths of $R_\star=4.9$ kpc, $z_\star=0.93$ kpc, $R_{\rm dust}\approx 4$ kpc, and $z_{\rm dust}=0.22$ kpc. In our simulations, we adopt the same scalelengths, but note that we use an exponential distribution in z as opposed to sech^2. We also include a bulge with $r_b=1.0$ kpc, $r_{\rm cut}=2.5$ kpc, and a bulge to total luminosity ratio of 0.1. As with NGC 4565 we use a vertical optical depth at V of $\tau_{\rm pole}=1$. These parameters reproduce the large scale flux contours, but are unable to match the fine structure present in the high resolution WIYN images (Howk & Savage 1997).

Although the V and H band model flux images in Figs. 2(a) and 2(b) reproduce the large scale flux images, the predicted polarimetric structure is very different from what is observed both in the optical (Scarrott & Draper 1996; Fendt *et al.* 1996) and in the IR (Jones 1997). Our model predicts very small polarizations that are parallel to the dust lane in the inner regions and perpendicular in the outer scattering

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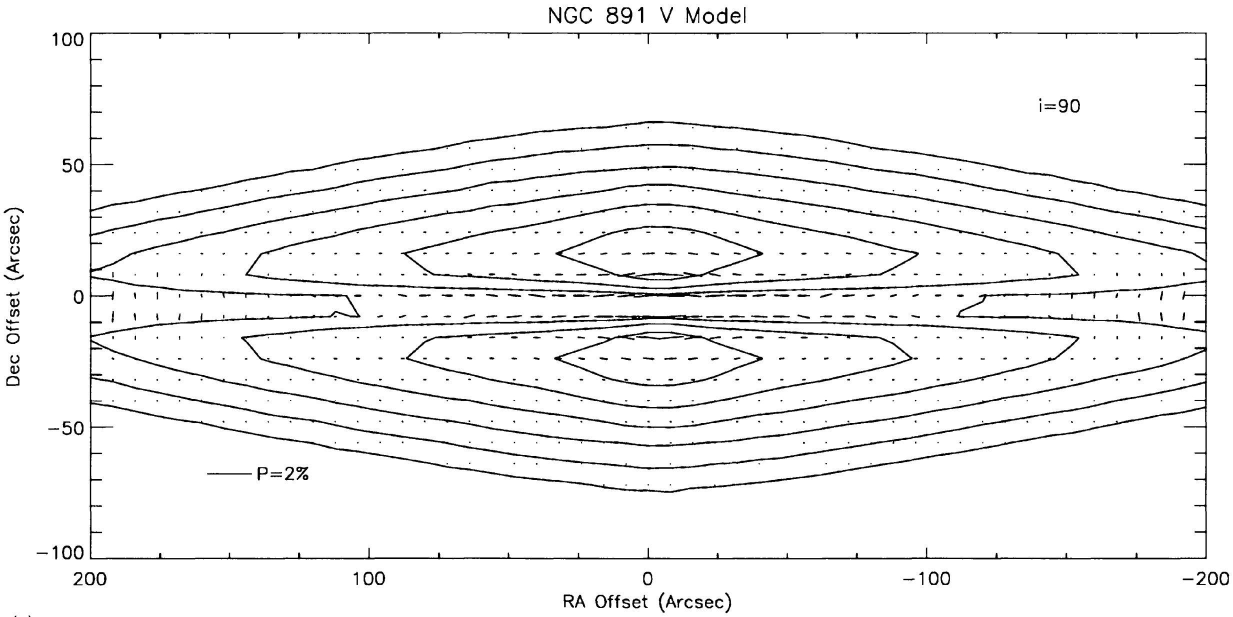
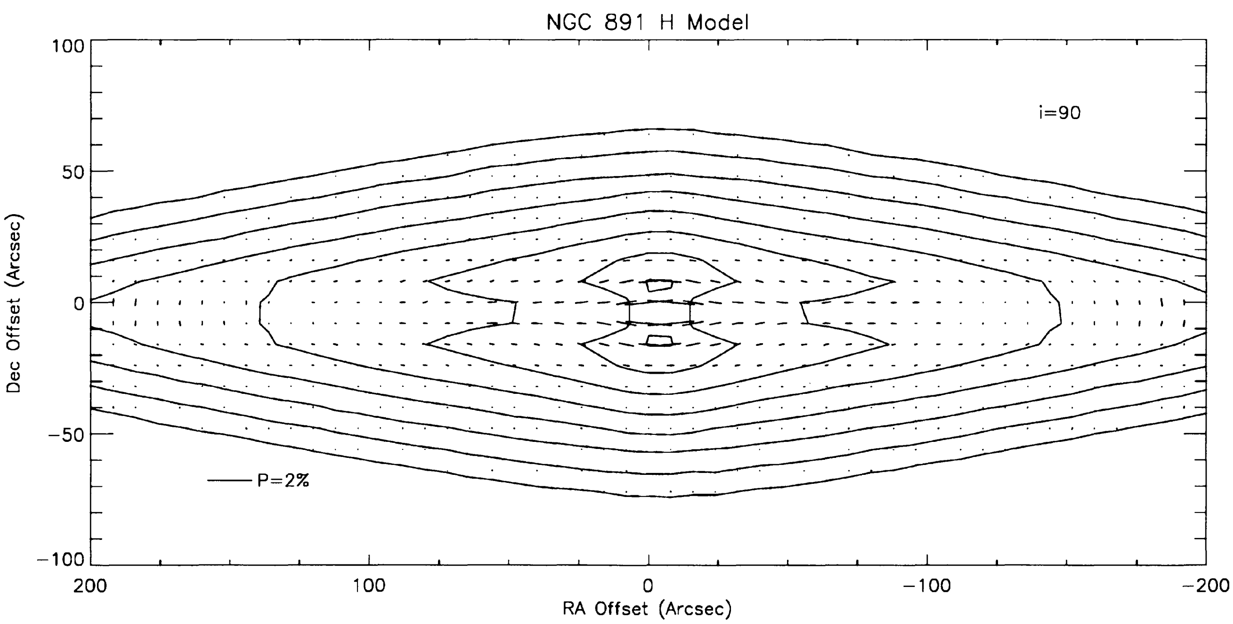


(a)



(b)

FIG. 2. (a) V band model of NGC 891 ($i=90°$). Notice the low polarization levels away from the dust lane since emission from these regions has very little dust to traverse. (b) H band model of NGC 891 ($i=90°$). As with the NGC 4565 models, the dust lane is weaker going from V to H and the polarization level is smaller.

dominated regions. Outside the dust lane, the polarization is negligible for this edge-on simulation. This occurs because the stellar scaleheight is much larger than the dust scaleheight. For edge-on viewing of high galactic latitudes, we are therefore viewing stars through a very small dust layer and hence the polarization arising from scattering or dichroic extinction is low. In Figs. 2(c) and 2(d) we show the same model, but viewed from an inclination of 85°. Once again we see small polarizations parallel to the dust lane, scattering polarization at large radii, and negligible polarization outside the dust lane.

Both these sets of models are in contrast to the H band observations which show significant polarization structures outside the dust lane (Jones 1997). In the optical polarization maps, Scarrott & Draper (1996) cite similar polarimetric structures as evidence for large scale *vertical* magnetic fields. This conclusion is also reached from polarization observations at radio wavelengths. The H band polarization is par-

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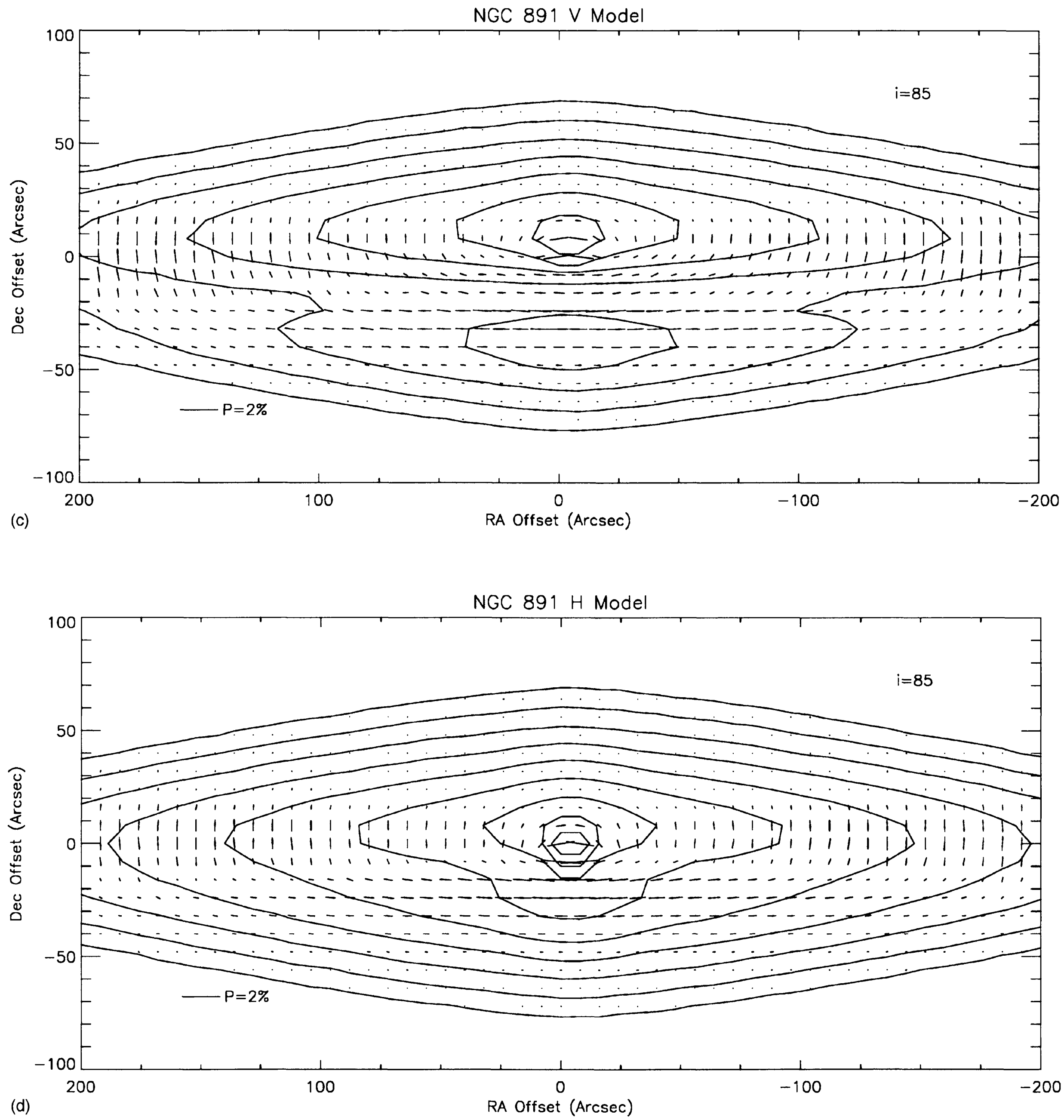

FIG. 2. (c) *V* and (d) *H* band model images of NGC 891 for $i=85°$. At this lower inclination we see extended regions of dichroic polarization in the lower halves of the images due to stellar emission from these regions passing through the galactic plane.

allel to the dust lane in some places and shows departures from this structure elsewhere. Similar patterns are evident in the optical polarization. The lack of coherent polarimetric structure within the dust lane is presumably due to the non-uniformity of the magnetic field geometry and hence lack of alignment of the dust grains over large size scales. The high resolution optical images also support this hypothesis with many plumes and filamentary structures which are much more prevalent than in NGC 4565 (Howk & Savage 1997). It is therefore not surprising that our smooth, Milky Way-like model for the interstellar polarization, is unable to match the magnitude or pattern of the polarization in NGC 891. This polarimetric evidence suggests that the magnetic field geometry and grain alignment is very different in NGC 891 than in our own Galaxy.

4. DISCUSSION

By including bulge emission within our Monte Carlo radiation transfer codes, we have extended previous investigations of the polarization structure of external galaxies to include bulge plus disk systems. The radiation transfer

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includes polarization arising from dust scattering and interstellar polarization (dichroic extinction). Due to the large number of uncertainties relating to size, shape, orientation, and alignment of interstellar grains, we include the interstellar polarization in our simulations using empirical relations between polarization and optical depth observed in the Milky Way. We further assume that the magnetic fields that align the dust grains are toroidal within the galactic disk. This then yields dichroic polarization that is parallel to the disk for highly inclined galaxies. Our models predict the correct qualitative behavior of the polarization patterns in external galaxies, with polarizations parallel to the disk within the dust lane, null points at the locations where scattering and dichroic polarization cancel, and polarization vectors perpendicular to the disk outside of the densest regions of the dust lane.

As a direct application of our techniques, we have attempted to model two edge-on galaxies that exhibit significant optical dust lanes. Our V and H band models of NGC 4565 and NGC 891 successfully reproduce the large scale features such as the dust lanes in the flux images. However, the smooth, axisymmetric dust and stellar distributions in the models are unable to reproduce the detailed structure present in the high resolution WIYN images (Howk & Savage 1997). We find that we are able to model the optical and IR polarization structure of NGC 4565 with the Milky Way polarization–optical depth relation and a toroidal magnetic disk field. Our models fail to reproduce the polarization observed in NGC 891, which displays significant polarization structures outside the dust lane. These polarimetric structures are interpreted in terms of magnetic fields that have been pulled vertical to the disk, perhaps as a result of massive outflows associated with star formation or supernovae injecting dust and gas into the halo. High resolution optical images provide further evidence that our smooth dust density and magnetic field structure is inappropriate for NGC 891. The high resolution WIYN image of NGC 891 exhibits much more activity within the dust lane than is present in the image of NGC 4565. Based on this polarimetric modeling, we conclude that NGC 4565 resembles our own Galaxy closer than does NGC 891. This is inferred from the success of incorporating the Jones *et al.* (1992) interstellar polarization parameterization into our model and our adoption of a large scale magnetic field parallel to the disk (as observed in the Milky Way).

We have demonstrated in this paper that the polarization data available for external galaxies enables us to obtain information about the large scale structure of galactic magnetic fields. Our models appear to be very successful in reproducing the polarization structure in bulge galaxies with relatively undisturbed dust lanes. Within galaxies such as NGC 4565, the magnetic fields seem to be coherent over large size scales within the disk, and the polarization scales with optical depth in the same way as it does in the Milky Way. In galaxies like NGC 891, that exhibit violent activity within their dust lanes, our models with smooth, large scale toroidal magnetic fields, and a Milky Way interstellar polarization–optical depth relation fail to match the polarization observations. For these galaxies, the magnetic fields lack any large scale toroidal structure within the disk and display evidence for vertical field structure. However, the polarimetric data we have based our modeling on does not approach the level of detail available for the Milky Way where we can map out complex field patterns (e.g., Mathewson & Ford 1970; Zweibel & Heiles 1997). As higher resolution imaging polarimetry becomes available, we will be able to perform more extensive modeling to determine the detailed small scale structure of galactic magnetic fields.

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