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THE OPACITY OF SPIRAL DISKS

A. BOSMA,[1] Y. BYUN,[2] K. C. FREEMAN,[2] AND E. ATHANASSOULA[1]

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ABSTRACT

The opacity of the disks of spiral galaxies can be evaluated by studying the gaseous component in edge-on galaxies in several wavelength regions. By combining data of the galaxy NGC 891 at 21 cm (H I), 2.6 mm (CO), and Hα, we show that the outer regions are transparent, while the inner regions, out to the radius to which CO is detected, could be optically thick. For the small galaxy NGC 100, such data indicate that this galaxy is by and large transparent, despite the presence of dust patches in the optical image. These results confirm the claim that spiral galaxies are transparent, at least in the outer parts, and clearly contradict the claim by Valentijn (1991) that the dark matter in spiral galaxies resides in the disk, in the form of absorbing clouds particularly abundant in the outer parts.

Subject headings: galaxies: ISM — galaxies: kinematics and dynamics — galaxies: spiral

1. INTRODUCTION

Several authors have recently suggested that the disks of spiral galaxies may be optically thick (Burstein & Lebofsky 1986; Disney, Davies, & Phillipps 1989; Davies 1990; Valentijn 1990). Valentijn (1991; also Gonzalez-Serrano & Valentijn 1991) has further proposed that the dark matter required to maintain the high rotation velocities in the outer parts of disk galaxies is just the same absorbing material which makes the disks optically thick.

Several studies have contested Valentijn's work, both his extreme proposal that the dark matter is in absorbing clouds in the disk, and his position concerning the amount of opacity in spiral disks. Cesarsky et al. (1991), Davies (1991), and Huizinga & Van Albada (1992) have all addressed Valentijn's statistics, and conclude that internal extinction is important only in the inner parts of spiral galaxies. However, Burstein, Haynes, & Faber (1991) argue that though the dark matter problem may not be solved in Valentijn's way, there is still evidence for spiral disks being essentially optically thick at the radius of the 25th mag arcsec^{-2} B isophote. A correspondence in Nature (1992 March 12, p. 114) between Disney and Burstein et al. shows that this matter is not yet settled.

In this *Letter*, we will test the transparency of disk galaxies directly, independent of statistical studies, by comparing optical emission-line rotation curves of two edge-on galaxies, NGC 100 and NGC 891, with their 21 cm line kinematics. These data show that the H I layer of NGC 100 is transparent at Hα. For NGC 891, the outer regions are again transparent; comparison with CO observations suggests that the inner parts of this galaxy may be optically thick. Results for other edge-on galaxies using published data are also presented.

2. A TRANSPARENCY TEST FOR EDGE-ON GALAXIES

Goad & Roberts (1981) have pointed out that the Hα rotation curves of edge-on disk galaxies can be used to indicate their optical depth. Independent of the true shape of their rotation curves, optically thick edge-on galaxies should show apparent solid body rotation curves in Hα, because the observed Hα emission then comes from ionized gas at the near edge of the optical disk.

To quantify this idea, we compare the Hα rotation curves of edge-on disk galaxies with their position-velocity diagrams obtained from 21 cm line observations. At 21 cm, optical thickness effects are essentially confined to the high-density clumps in the neutral gas, which have a very low filling factor (cf. data for M31; Braun 1991), so that we expect the full radial velocity range to be observed, even in the edge-on case. If the disks are not optically thick at Hα, then the Hα emission comes from regions along the entire line of sight through the disk and the peak velocities of the Hα profiles should lie close to the high-velocity envelope of the 21 cm position-velocity diagram. (This holds even if the optical depth approaches unity at the point where the line of sight passes closest to the center of the galaxy.) If the disks are optically thick at Hα out to some radius R, at which the true rotational velocity is V, then we would expect to see an approximately solid body Hα rotation curve rising to velocity V at projected radius R.

If the intrinsic rotation curve of the galaxy is approximately solid body over the region of Hα emission, we cannot say anything about the optical depth. However, from a change of gradient in the observed optical rotation curve of an edge-on galaxy, we can infer directly that the galaxy is transparent at radii larger than the radius at which the gradient changes, without any need for H I data.

To illustrate the expected Hα rotation curves, we have made radiative transfer computations for a simple descriptive model of the dust and Hα emission distribution in a typical disk galaxy. Our radiative transfer code is based on that of Kylafis & Bahcall (1987), includes absorption and scattering, is generalized to galaxies viewed from any orientation, and has been used for an extensive study of dust in disk galaxies, to be fully described elsewhere.

In our model, the space density distribution of the Hα emission $L(R, z)$ and the absorbing dust $A_\lambda(R, z)$ in galactocentric (R, z) coordinates are assumed exponential in both R and z, with scale lengths h_g, h_d and scale heights h_{gz}, h_{dz} for the Hα-emitting gas and the dust, respectively. Since the dust and Hα emission are both concentrated to the midplane of a spiral galaxy, we assume $h_{gz} = h_{dz}$. For the scale length, we considered two possibilities: one in which the model galaxy has a scale length of 5 kpc and a scale height of 150 pc for both dust

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[1] Observatoire de Marseille, 2 Place Le Verrier, F-13248 Marseille Cedex 4, France.

[2] Mount Stromlo and Siding Spring Observatories, Private Bag, Weston Creek P.O., A.C.T., Australia.

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and Hα, and one in which the scale length of the dust is a factor of 3 larger, to mimic the situation envisaged by Valentijn's extreme hypothesis. The opacity of the disk is characterized by the total face-on optical depth at the center in the visual passband, $\tau_V(0) = \int_{-\infty}^{\infty} A_V(0, z)dz$.

For the nearly edge-on galaxies considered here, the main contribution of scattering is to remove light from the line of sight; pure absorption is by far the dominant factor in the radiative transfer for the observed radiation. Our models show that scattering makes only a few percent change to the location of the loci of unit optical depth within the model galaxies and has an imperceptible effect on the predicted Hα rotation curves. Scattering becomes more significant only as a galaxy is seen more face-on. For the radiative transfer computations shown in Figure 1, we have therefore included pure absorption only, without scattering. The interstellar extinction law of Rieke & Lebofsky (1985) has been adopted for the wavelength dependence of the absorption. Each light element along the line of sight carries its own kinematical information, and its contribution is weighted by the amount of surviving light after dust extinction. The expected rotation curve is derived from the line-of-sight velocity profile at each projected radius, after convolution with Gaussian distributions to represent turbulence in the gas ($\sigma = 8$ km s^{-1}) and the point-spread function of the spectrograph ($\sigma = 28$ km s^{-1}, which is typical of the medium-resolution spectrographs used for these observations). This convolved velocity distribution is then correlated with a template Gaussian to derive the rotational velocity.

Figure 1 shows results from our models, in the case of equal scale lengths for dust and gas. We note two features in Figure 1: (1) There is a trend toward apparent solid body Hα rotation for the edge-on galaxy as the optical depth increases, and (2) the effect of extinction on the apparent rotation curve is already much reduced for a model that is only 5° from edge-on. The results are qualitatively similar when the scalelength of the dust is 3 times larger, corresponding to the more extreme extinction envisaged by Valentijn. In this case, the effects of absorption on the rotation curves are stronger: at $i = 90°$, the apparent rotation curve is solid body for all $\tau_0 \geq 0.5$, and even at $i = 85°$, the effects of extinction are still apparent.

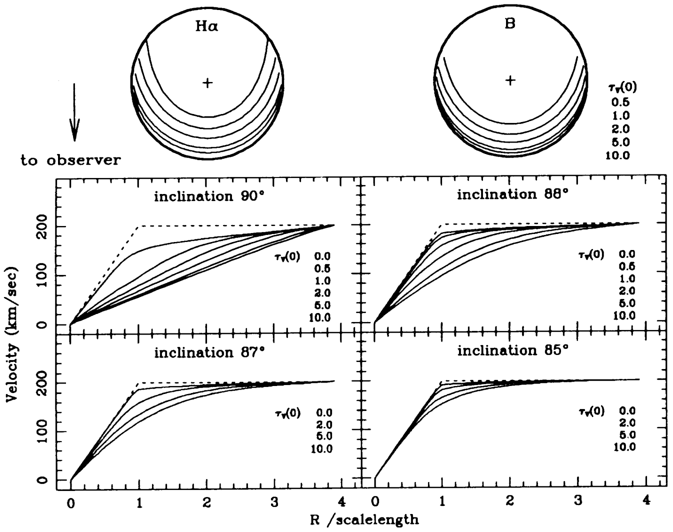

FIG. 1.—Loci of unit optical depth at Hα and B in the plane of the model galaxy (*upper panel*), and the predicted Hα rotation curves (*lower panels*) at several nearly edge-on inclinations, each for a range of values for the face-on central optical depth τ_0. This model has equal scale lengths for dust and gas. A circle with radius 4 scale lengths is shown for reference.

3. OBSERVATIONS

3.1. *NGC 100 and Other Small Sc Galaxies*

For the edge-on galaxy NGC 100, we have obtained H I data with the VLA in its B and C configurations, which have a resolution, after smoothing, of 8″. An Hα spectrum was obtained for us by R. Augarde, using the 193 cm telescope at the Observatoire de Haute Provence, and its Carelec spectrograph, equipped with an RCA CCD detector. An independent Hα spectrum was obtained with the ANU 2.3 m telescope at Siding Spring and its double beam spectrograph, with a photon-counting array as detector. The optical data are in excellent agreement. The principal information is shown in Figure 2, where the Hα velocities are superposed on the H I position-velocity diagram along the major axis. Since the emission-line velocities all lie on the upper envelope of the H I position-velocity diagram, it is clear at once that this galaxy must be transparent at Hα. The narrow band of the emission-line data indicates that the H II regions are smoothly distributed throughout the plane of NGC 100; as Goad & Roberts (1981) pointed out, a jagged Hα position-velocity curve would be seen if the distribution of H II regions were patchy.

It is crucial for our test to know the inclination of the galaxy. For NGC 100 we have determined this by modeling the observed H I channel maps and conclude that the inclination is most likely 87° or larger. Furthermore, Hα spectra perpendicular to the major axis of the galaxy fail to indicate the expected behavior in radial velocity for non–edge-on galaxies in a clear manner. Unfortunately, the signal-to-noise ratio of these data is not very large. Guthrie (1992) gives an inclination of 88° for this galaxy.

We have observed NGC 100 in the CO (1–0) and (2–1) lines with the 30 m IRAM telescope. No signal was detected: the rms noise level reached on the central position of the galaxy was 6.5 mK at $\lambda = 2.6$ mm and 17.6 mK at $\lambda = 1.3$ mm (main beam temperature scale; cf. Mauersberger et al. 1989). Using a conversion factor CO–H$_2$ of $M_{\mathrm{H}_2} = 3.7L_{\mathrm{CO}}$ (e.g., Combes 1991), an expected velocity width of 100 km s^{-1}, and a 2 σ upper limit at 2.6 mm, we derive an upper limit of 7.3×10^6

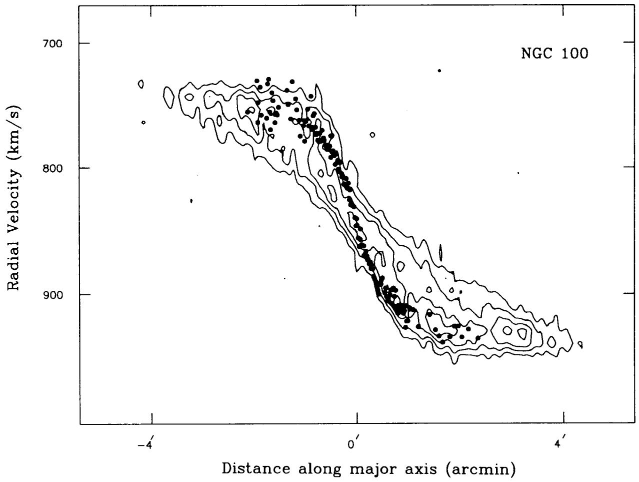

FIG. 2.—H I position-velocity diagram along the major axis of NGC 100, with superposed (*dots*) the observed Hα-velocities. The contour interval is 0.5 mJy beam^{-1} (=4.7 K) and the lowest contour is 0.5 mJy beam^{-1}.

$M_\odot$ of molecular gas in the central parts of the galaxy. This can be compared with the total amount of H I gas, which is 1.9×10^9 $M_\odot$ (assuming a distance of 12.5 Mpc to NGC 100; cf. Tully 1988), and roughly 7×10^7 $M_\odot$ within the central 23″ area (the beam size of the 2.6 mm CO data).

We thus conclude that NGC 100, despite the presence of some dust patches in the optical images, is by and large transparent. Optical data for the very thin edge-on "integral-sign galaxy" UGC 3697, from Goad & Roberts (1981) and Marquez & Del Olmo (1991), show that its rotation curve rises very steeply in the inner 10″ and is flat thereafter. As discussed above, this characteristic behavior is sufficient evidence that this galaxy is transparent at Hα, at least at radii beyond the turnover point in the rotation curve.

These transparent galaxies are small systems, with typical rotation velocities of about 100 km s^{-1}. For larger galaxies the internal absorption may be different, since their mean metallicities are probably higher. We therefore examine data for some larger spirals.

3.2. *NGC 891 and Other Large Spirals*

For NGC 891, position-velocity diagrams along the major axis are available for H I (Sancisi & van Albada 1987) and CO (Sofue, Nakai, & Handa 1987). The H I in the plane of this galaxy is distributed in a broad annulus, with a mean radius of about 4′ (van der Kruit 1981), which appears as the solid body ridge in the H I position-velocity diagram. Optical velocities have been measured by Keppel et al. (1991) (Hα) and Bottema et al. (1991) (Hβ), and we have measured the optical rotation from Hβ and the green [O III] lines using the Steward Observatory 2.3 m telescope, the Boller & Chivens spectrograph, and a TI CCD. The various optical measurements are in excellent agreement. Figure 3 shows our data and those of Keppel et al. superposed on the position-velocity diagrams: contrary to the cases discussed above, the optical velocities lie on the H I ridge rather than along the high-velocity envelope. For the CO data, the upper envelope in the position-velocity plane (i.e., the rotation curve) is similar to that of the H I, but the ridgeline is significantly steeper. Therefore most of the CO emission comes from regions inside the H I annulus.

The data for NGC 891 have two alternative interpretations. (1) The optical H II regions are distributed throughout the disk of NGC 891, and the galaxy is optically thick in the region of CO emission within the H I annulus. (2) The optical H II regions lie near the peak of the H I annulus and at larger radii, in which case we have no information about the opacity of NGC 891 along lines of sight that pass within about 4′ of the center. We cannot distinguish between these two possibilities. However, in either case, it is clear that at optical wavelengths, the plane of NGC 891 is transparent beyond about 4′ ($\approx 0.5R_{25}$) from its center.

For the edge-on galaxy NGC 5907 the Hα data from Carozzi-Meyssonnier (1977) show the same behavior in the 21 cm position-velocity diagram published by Sancisi & Van Albada (1987) as we found for NGC 100. Although this galaxy has an inclination of 87° (van der Kruit & Searle 1982), our test is still sensitive enough to show clearly that the outer H I layers, which are thought to be thicker and flaring outward, are transparent. No CO emission has been detected from this galaxy (Verter 1985).

4. DISCUSSION

By comparing optical and H I kinematics of several edge-on spiral galaxies, we have shown that the outer parts of the disks, where the H I is the dominant detected gas component, are transparent in all our examples, contradicting Valentijn's (1991) suggestion that the dark matter is in the form of absorbers which are more abundant in the outer disks of spiral galaxies. For most of our examples, the transparency is seen throughout the observable disk, but one large galaxy (NGC 891) could be optically thick out to about $0.5R_{25}$ from its center.

The observations of NGC 891, a large Sb galaxy, suggest that the inner parts of some spirals may be optically thick, and the outer parts optically thin. (This conclusion agrees with results from the statistical studies by Cesarsky et al. 1991 and Huizinga & Van Albada 1992.) Since the CO emission from NGC 891 is very different from the others, we speculate that any optical thickness of the inner regions of large galaxies is related directly to the amount of molecular material present. A comparison of H I and CO kinematics with optical rotation data from emission lines at widely different wavelengths (e.g., [O II] λ3727, Hα, Brγ) would allow more refined measurements of the internal absorption in edge-on galaxies.

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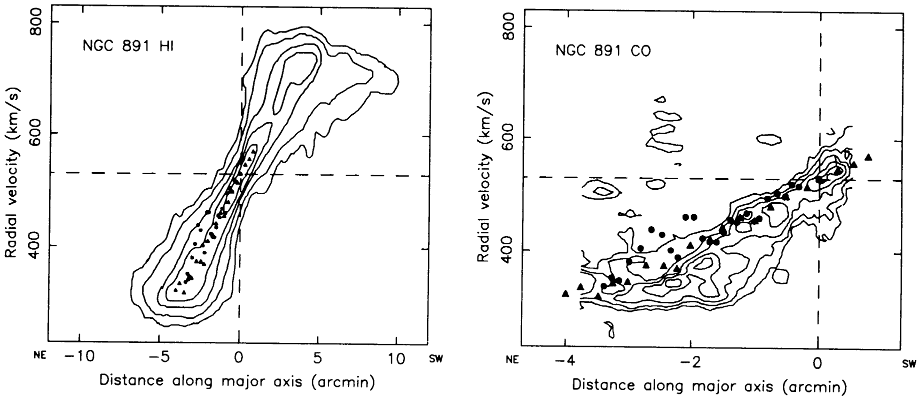

FIG. 3.—*Left:* H I position-velocity diagram of NGC 891 (cf. Sancisi & Van Albada 1987), with the optical data superposed. *Right:* CO position-velocity diagram (cf. Sofue et al. 1987), again with the optical data. Dots are our data; triangles are data from Keppel et al. (1991).

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