NGC 891: A SUMMARY OF OBSERVATIONS

R. J. ALLEN
Space Telescope Science Institute
3700 San Martin Drive, Baltimore, MD 21218

S. SUKUMAR
Astronomy Department and
National Center for Supercomputing Applications
University of Illinois, Urbana IL 61801

ABSTRACT. Three questions are posed, the answers to which are relevant to our understanding of the physical processes which shape the radio continuum morphology of normal spiral galaxies. Observations of the edge-on galaxy NGC 891 have been made for many years by several groups with the intention of contributing at least partial answers to these questions. We review here the work which we have recently done on this subject.

1. INTRODUCTION

What can we learn about the subject of this symposium, "The Interstellar Disk-Halo Connection in Galaxies", from detailed observations of the radio continuum emission from a galaxy seen edge-on? We may break this (too) general question down into three specific questions:

1. Is there any relationship between the radio continuum surface brightness and the optical emission at high Z?

2. How does the spectrum of the radio continuum emission vary with Z?

3. What is the orientation of the magnetic field at high Z?

Before we can understand why the answers to these three questions may be interesting, we have to review some facts about the nature of the nonthermal radio continuum emission from the interstellar medium (cf. for example Ruzmaikin, Shukurov, and Sokoloff 1988):

1. The synchrotron volume emissivity η at radio frequency ν for a power-law distribution of relativistic elecrons $N(E) = N_0 E^{-\gamma}$ in a magnetic field H is $\eta \sim N_0 H_{\perp}^{1-\alpha} \nu^{\alpha}$ where $\alpha = (1-\gamma)/2$ is typically in the range -0.6 to -1.3 or so. The

H. Bloemen (ed.), The Interstellar Disk-Halo Connection in Galaxies, 287–294.

https://doi.org/10.1017/S007418090008918X Published online by Cambridge University Press

electron energy loss rate is greater at higher energies, leading in general to a progressive steepening of the spectrum with age unless an efficient re-acceleration mechanism exists.

2. Synchrotron radio emission is highly (linearly) polarized, the degree of polarization $p_0 = (3\gamma + 3)/(3\gamma + 7) \approx 0.75$ for $\alpha \sim -1$ (i.e. $\gamma \sim 3$), and the direction of maximum intensity is perpendicular to the magnetic field.

3. The polarization observed at a linear size scale S where L > S > d is reduced if only part of the total field $\mathbf{H} = \mathbf{B} + \mathbf{b}$ is uniform (B) on scales of "L" and the rest random (b) on scales of "d", according to $p = p_0(B_\perp/H_\perp)^2$.

4. An unresolved, clumpy foreground "Faraday Screen" (or depolarizing material mixed in with the source) leads to a strong dependence of the degree of polarization p on wavelength. Typical model geometries lead to $p \sim \exp(-2R^2\lambda^4 L/d)$, with the rotation measure $R = 0.8 \times \int_l n_e H_\| dl$, for n_e in cm^{-3}, H in μG, l in pc, and λ in m. There is very little change in the direction of maximum polarization with λ at longer wavelengths in this situation (see e.g. Laing 1984, Cioffi and Jones 1980).

2. THE RADIO AND OPTICAL CONTINUUM EMISSION FROM NGC 891

The first high-resolution radio continuum observations of NGC 891 (Allen et al. 1978) made with the Westerbork Synthesis Telescope (WSRT) clearly showed the existence of two main components to the Z-distribution of the emission: a thin disk, which was barely resolved in the 7.2″ beam at 6 cm, and a thick disk with a FWHM of 76″ or 2.7 kpc (1′ = 2.1 kpc at an assumed distance of 7.2 Mpc). Figure 1 shows these features. Of the two components, the thin disk is the more extended along the major axis (see also Figure 1 in Sancisi and Allen 1979), and corresponds roughly with the main dust lane there.

The thick disk is quite "fat", and at first glance did not seem to correspond well with the optical light at high Z. However, prints of galaxy images made from telescope plates usually accentuate the discrete features and do not accurately reproduce the faint extended emission, so that a quantitative comparison is necessary to settle the matter. This was first carried out by Hu et al. (1987), using calibrated surface photometry of NGC 891 made at optical wavelegths by Van der Kruit and Searle (1981) and 20 cm continuum data obtained from unpublished WSRT HI synthesis observations by Sancisi. Owing to the limited radio sensitivity, Hu et al. had to average the data in strips parallel to the major axis. A correlation was found of the form $I_{opt}^{U'} \sim (I_{rad}^{21})^{1.05}$ over the range of from 7 to 35 mJy/arcmin^2. The optical U′ band covers the wavelength range 340-425 nanometers. This relation between the radio and optical emission is reminiscent of the result found for the total continuum power from normal galaxies of $P_{opt}^{B} \sim (P_{rad}^{21})^{1.0\pm0.2}$ in the survey by Hummel (1981).

More recently, a further improvement in the radio sensitivity has permitted a test of this correlation over a wider range of surface brightness (Allen et al. 1990).

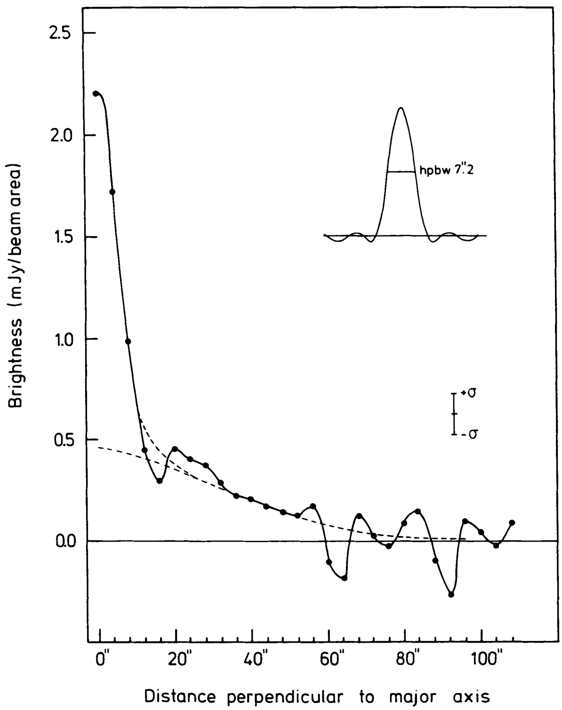

Figure 1. Distribution of radio surface brightness perpendicular to the major axis of NGC 891 at 6 cm obtained by averaging in strips 4′ long parallel to the major axis and 7.2″ wide. From Allen et al. 1978.

Star images were first cleared from a strip in the optical image 200″ × 24′ centered on the nucleus and stretching along the minor axis, and the zero level adjusted to the level at the extremities of this strip. The radio data required removal of a few discrete sources and a similar base-level re-adjustment. The data were smoothed to a common resolution (16″ × 12″ at PA = 0°) and registered to a common grid. The radio image could then be compared pixel-for-pixel with the optical data, at least down to 1 mJy/beam (excluding the optically-obscured central strip), and by averaging in 200″ strips parallel to the major axis the brightness limit could be lowered further to 20 microJansky/beam. The final result is shown in Figure 2. The data show a correlation which now extends over nearly three orders of magnitude in surface brightness and is of the form $I^{F}_{opt} \sim (I^{21}_{rad})^{1.2}$, covering a range in Z from 12″ to 140″ (420 pc to 4.9 kpc). The optical photometric F band used for this comparison covers the wavelength range 580-690 nanometers.

We can now answer the first question from the Introduction in the affirmative. In the thick disk at high Z above the optical obscuration of the plane of NGC 891, the radio surface brightness can be predicted from the optical surface brightness to within about a factor of 2. The result is surprising, given the complicated

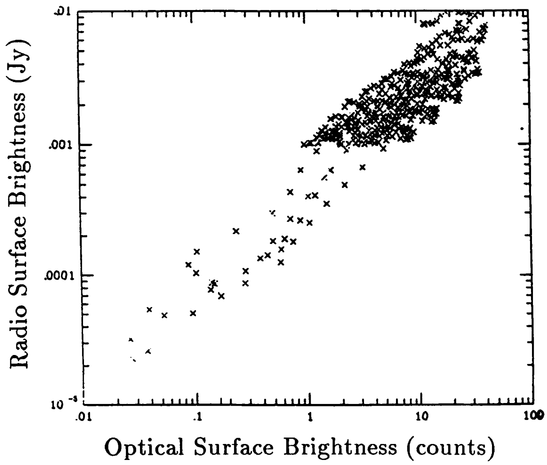

Figure 2. Correlation between the optical F band and the 21-cm radio continuum surface brightnesses in NGC 891. From Allen et al. 1990.

dependence of η on N(E) and H as recalled in the Introduction above. At the present time, the "standard theory" for the generation of the radio synchrotron emission does not couple η with the local density of starlight. Here is a challenge to the theoreticians.

Note that several other face-on galaxies (e.g. M51, Tilanus et al. 1988; NGC 6946, Van der Kruit et al. 1977) also show some degree of correlation between the nonthermal radio and the optical brightnesses, although the ratio I_{opt}/I_{rad} appears to vary a lot from one galaxy to another. The data for these other galaxies have also not been analyzed on a detailed pixel-by-pixel basis as has been done for NGC 891. Here is a challenge to the observers.

3. THE VARIATION OF SPECTRAL INDEX WITH Z

Using newer WSRT data at 6 cm and the 21 cm continuum data from Sancisi's HI synthesis, Allen and Hu (1985) showed that the two components identified earlier had distinctly different spectral indexes, and that there was no convincing case for a change of those spectral indexes with Z. Figure 3 shows the results of fitting the two-component model (right panel) to the data (left panel) averaged in strips parallel to the major axis. The model has the thin disk extending from $0 < Z < 15''$ ($0 < Z < 500$ pc) with $\alpha \approx -0.5$ and the thick disk dominating in the range $15'' < Z < 2'$ ($0.5 < Z < 4.2$ kpc) with $\alpha \approx -1$. There is some indication in the data that the spectral index of the thick disk steepens at still higher Z, but it is very difficult to be sure of this since the infamous "short spacing problem" in radio synthesis data can easily produce an artificial steepening.

Quite recently, Hummel et al. (1990) have presented new VLA observations of NGC 891 which support the simple two-component model of Allen and Hu. Figure 4 shows their VLA results and, although their resolution (40″) is not as good as that obtained by Allen and Hu (20″), the separation into two components is clearly

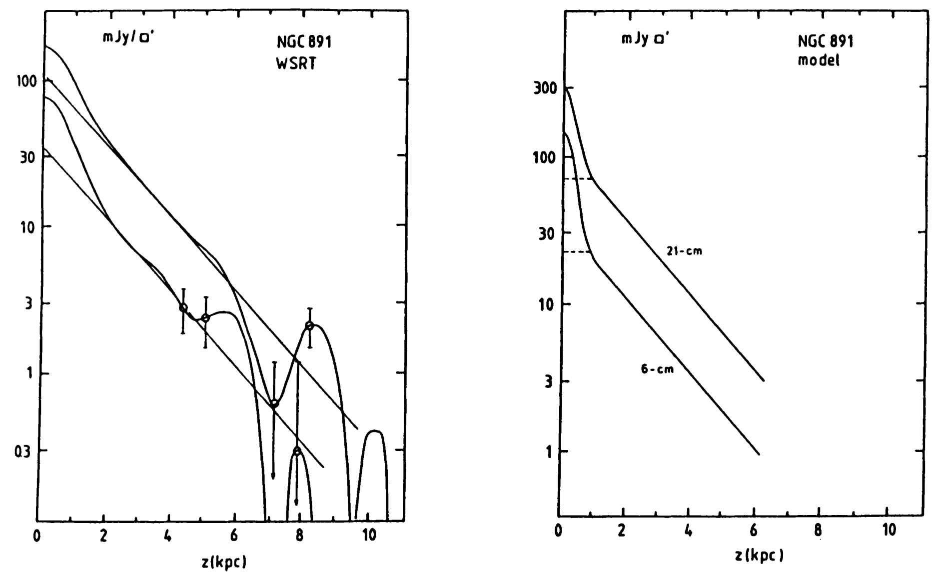

Figure 3. Z-distribution of surface brightness in NGC 891 at 6 and 21 cm observed with a 20″ beam (left panel), and the two-component model (right panel) with a thin and a thick disk which fits the data. From Allen and Hu 1985.

a very good approximation. The possible steepening at high Z is also seen, but the same caveats about the "missing short spacings" apply here as well.

Parenthetically, we would like to draw attention to two practical limitations which have adversely affected some observations, including our own. For the first example the earlier results of Allen et al. (1978) on the Z-variation of spectral index (cf. their Figure 6) gave an erroneous impression that the spectral index was steepening smoothly with increasing Z; this is a result of insufficient angular resolution. Secondly, even if the resolution is sufficient, the "short spacing problem" can also produce a spurious steepening of the spectral index above Z of about 45″ (cf. their Figure 5).

The second question from the Introduction is, therefore, to be answered in the negative. There is no convincing evidence that the spectral index of the thick disk steepens with increasing Z, at least up to 2′ (4.2 kpc) above the plane. There is a hint that the spectrum of the thick disk may steepen at still higher Z, but every time we look harder for this feature it recedes to greater Z distances. The flattening of the spectral index below Z of 15″ is a consequence of the increasing importance of the thin disk.

Note that some face-on galaxies also show little variation of their radio spectral indexes with radius (M51, Van der Kruit 1977; NGC 6946, Van der Kruit et al. 1977). The edge-on case is, however, especially tricky to explain in the "classical"

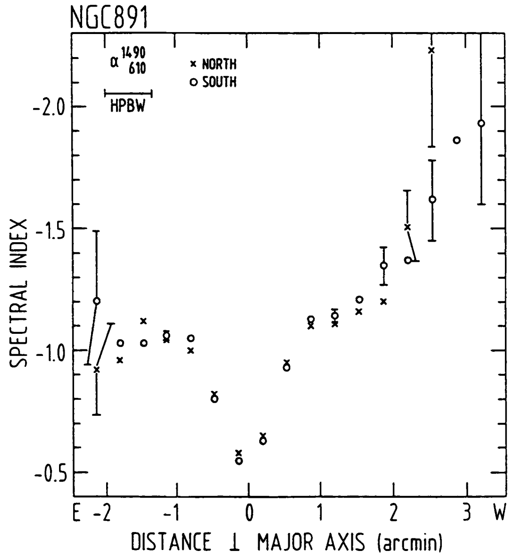

Figure 4. Radio continuum spectral index along the minor axis of NGC 891, from Hummel et al. 1990.

model, where the cosmic ray electrons are produced and accelerated in the plane and diffuse out of the plane losing energy along the way. One alternative is to postulate some mechanism for re-accelerating the electrons, but this mechanism would require some fine tuning in order to keep the spectral index substantially constant as the electrons diffuse over many kiloparsecs in Z.

4. THE ORIENTATION OF THE MAGNETIC FIELD AT HIGH Z

Hummel and Dahlem (1990) have recently reviewed the available results concerning the direction of the magnetic field in NGC 891 and NGC 4631 at high Z. In the case of NGC 4631, there is a modest amount of polarization (about 10%) observed at 20 cm wavelength in the thick radio disk at Z$\sim$ 3$'$ (4.5 kpc at a distance of 5.2 Mpc) and a clear indication that the magnetic field is oriented perpendicular to the plane, which the authors take as supporting the galactic wind model for the transport of cosmic rays out of the plane. In NGC 891 the situation as reported by Hummel and Dahlem is less clear, with less large-scale order apparent and no great degree of uniformity in the field direction over the thick disk.

At 6 cm any effects of Faraday rotation and depolarization will be considerably reduced (cf. point 4 in the Introduction), so we may expect that the observed degree of polarization would be greater and the position angle of maximum polarization would be a more accurate indicator of the true direction of the magnetic field. Figure 5 shows the distribution of total intensity in NGC 891 which we have recently observed with the VLA at 6 cm. The brightest peak in the total intensity contours

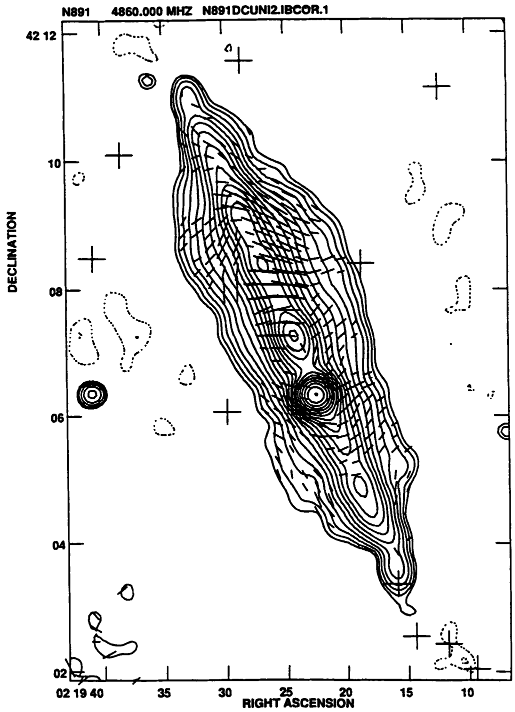

Figure 5. Contours of the total radio continuum emission at 6 cm from NGC 891, starting at 150 microJanskys beam^{-1} and increasing by $2^{N/2}$. The line segments have lengths proportional to the linearly polarized surface brightness at their centers (1″ on the plot is 8.33 microJanskys beam^{-1}), and directions indicating the position angle of maximum polarization. The restoring beam width is 20″ (FWHM, circular), and the r.m.s. noise is about 25 microJanskys beam^{-1}.

is SN 1986J, located about 1′ southwest of the nucleus. The polarization, indicated by the short line segments, reaches more than 30% in the thick disk. The direction of the magnetic field, which is perpendicular to the line segments, shows a large-scale symmetry not visible on the 20-cm map of Hummel and Dahlem, with the field largely parallel to the plane in the central regions of the galaxy and an indication that the lines of force "flare" upwards out of the disk at larger radial distances.

A comparison of our 6 cm data with the 20 cm data shown by Hummel and Dahlem reveals surprisingly little rotation of the direction of maximum polarization with wavelength. From this, and the larger degree of polarization at 6 cm, we conclude that the thick disk of NGC 891 is substantially "Faraday thick" at 20 cm, becoming progressively thin as we move to 6 cm and shorter wavelengths. By way of illustration, we can do the computation for a Z height of 30″ (1 kpc). At this height, the electron density from the observations of Rand et al. (1990) and Dettmar et al. (1990) is about 0.01 - 0.03 cm^{-3}. For L = 10 kpc, d = 100 pc, H

$= 2\ \mu G$ and $B = b = \sqrt{2}\mu G$ we find from the equations in the Introduction that R(regular) = 200 rad m^{-2} and R(random) = 2 rad m^{-2}. The intrinsic degree of polarization $p \approx 40\%$, is hardly affected at 6 cm, but is reduced to 10% at 20 cm.

So we have the answer to the third question posed in the Introduction: The magnetic field in the thick disk of NGC 891 is oriented largely parallel to the plane in the central regions of the galaxy, possibly curling upwards out of the plane at larger radii. The morphology of the polarization is strongly affected by Faraday depolarization, which can explain not only the increase of p with Z but also the great differences in the appearance of the polarized emission at 6 and 20 cm. A more detailed description of these results and a discussion of the implications is in preparation.

ACKNOWLEDGMENTS

We are grateful to Rainer Beck for sharing his unpublished results with us, and to Ko Hummel for helpful discussions.

REFERENCES

Allen, R. J., Baldwin, J. E., and Sancisi, R. (1978), *Astron. Astrophys.,* **62,** 397-409.

Allen, R. J., Sukumar, S., Hu, F. X., and Van der Kruit, P. C. (1990), in *Galactic and Intergalactic Magnetic Fields,* ed. R. Beck, P. P. Kronberg, and R. Wielebinski (Kluwer, Dordrecht), 223-224.

Allen, R. J., and Hu, F. X. (1985), in *New Aspects of Galaxy Photometry,* ed. J.-L. Nieto (Springer, New York), 293-296.

Cioffi, D. F., and Jones, T. W. (1980), *Astron. J.,* **85,** 368-375.

Dettmar, R.-J. (1990), *Astron. Astrophys.,* **232,** L15-L18.

Hu, F. X., Allen, R. J., Van der Kruit, P. C., and You, J. H. (1987), *Astrophys. Space Science,* **135,** 389-392.

Hummel, E. (1981), *Astron. Astrophys.,* **93,** 93-105.

Hummel, E., Dahlem, M. (1990), in *Galactic and Intergalactic Magnetic Fields,* ed. R. Beck, P. P. Kronberg, and R. Wielebinski (Kluwer, Dordrecht), 219-222.

Hummel, E., Dahlem, M., Van der Hulst, J. M., and Sukumar, S. (1990), *Astron. Astrophys.* (submitted).

Laing, R. A. (1984), in *Physics of Energy Transport in Extragalactic Radio Sources,* ed. A. H. Bridle and J. A. Eilek (NRAO, Green Bank) 90-98.

Rand, R. J., Kulkarni, S. R., and Hester, J. J. (1990), *Astrophys. J.,* **352,** L1-L4.

Ruzmaikin, A. A., Shukurov, A. M., and Sokoloff, D. D. (1988), *Magnetic Fields of Galaxies* (Kluwer, Dordrecht).

Sancisi, R., and Allen, R. J. (1979), *Astron. Astrophys.* **74,** 73-84.

Tilanus, R. P. J., Allen, R. J., Van der Hulst, J. M., Crane, P. C., and Kennicutt, R. C. (1988), *Astrophys. J.,* **330,** 667-671.

Van der Kruit, P. C. (1977), *Astron. Astrophys.,* **59,** 359-366.

Van der Kruit, P. C., Allen, R. J., and Rots, A. H. (1977), *Astron. Astrophys.,* **55,** 421-433.

Van der Kruit, P. C., and Searle, L. (1981), *Astron. Astrophys.,* **95,** 116-126.