

Deciphering the radio-star formation correlation on kpc scales

IV. Radio halos of highly-inclined Virgo cluster spiral galaxies

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Received ; accepted

ABSTRACT

In addition to the radio continuum emission of the thin galactic disk, vertically extended emission is ubiquitous in starforming disk galaxies. This halo emission can represent an important fraction of the total emission of the galaxy. The cosmic ray electrons (CRE) responsible for the radio continuum emission are produced within the thin disk and transported into the halo. They might interact with the warm neutral and ionized medium, which are also present in the halo region. We made an attempt to reconstruct the radial properties of radio continuum halos in nearly edge-on galaxies where the star formation rate (SFR) distribution can be deprojected and the vertical radio continuum emission is well distinct from the disk emission. The deprojected SFR distribution is convolved with a Gaussian kernel to take CRE diffusion within the galactic disk into account and a vertical profile of the radio continuum emissivity is added to the disk emission. The three-dimensional emission distribution is then projected on the sky and compared to VLA radio continuum observations at 20 and 6 cm. We found that overall the halo emission contains information on the underlying distribution of the star formation rate. The majority of our galaxies show flaring radio continuum halos. Except for one galaxy, our Virgo galaxies follow the trend of increasing effective height with increasing radio continuum size found by the CHANG-ES collaboration. We confirm that radio continuum halos can represent a significant fraction of the total radio continuum emission of a starforming spiral galaxy. At 20 cm and 6 cm between 30 and 70 % of the total radio continuum emission originate in the halo. We propose a halo classification based on the height ratio and SI between 20 and 6 cm. If we interpret the vertical structures of the large-scale magnetic field within the disk-halo and halo types as a sign of a galactic outflow or wind, all galaxies except one most probably harbor an advection-dominated halo.

Key words. galaxies: ISM – galaxies: magnetic fields – radio continuum: galaxies

1. Introduction

The vertical scale heights of the different phases of the Galaxy's interstellar medium (ISM) vary between ~ 70 pc for the molecular gas, ~ 140 pc for the cold neutral medium, and ~ 400 pc for the warm neutral medium (Boulares & Cox 1990). In addition, the warm ionized medium (WIM) or diffuse ionized gas (DIG) extends to a height of ~ 1 kpc (e.g., Haffner 2009). Beyond the Galaxy, similar distributions of the DIG have been observed in many nearby disk galaxies (e.g., Dettmar 1990; Rand et al. 1990; Zurita et al. 2000; Levy et al. 2019). Diffuse radio continuum emission, which is generally associated to the high-altitude WIM (Krause et al. 2018) and is called a radio continuum halo. The mechanism of the radio continuum emission is synchrotron emission stemming from cosmic ray (CR) electrons interacting with the magnetic field of a galaxy. Cosmic ray particles are mainly produced in supernova shocks via Fermi acceleration. However, the relativistic electrons do not stay at the location of their creation. They propagate either via diffusion, or by streaming with the Alfvén velocity. In addition, cosmic ray electrons can be transported into the halo by advection, meaning a galactic wind or outflow. The CHANG-ES project (Irwin et al. 2012) showed that for starforming disk galaxies the vertical transport of CR electrons is mostly caused by advection (Heesen 2021; Irwin et al. 2024): only two out of eleven analyzed CHANG-ES galaxies show a diffusion-dominated radio

halo. The best-known discriminator thus far is the star-formation rate surface density. Galaxies at low star formation rate (SFR) surface densities have diffusive halos. The heights of the radio halos are set by either diffusion and advection together with CR electron escape or synchrotron losses. The typical scale height of radio continuum halos is about 1 kpc (Krause et al. 2018), very close to that of the WIM.

The CHANG-ES collaboration studied the radio continuum halos of edge-on galaxies ($i = 76-90^\circ$) by fitting Gaussian and exponential functions to the vertical profiles of the radio continuum emission at 6 (C-band) and 20cm (L-band). The CHANG-ES project is described in Irwin et al. (2012) and details about the first data release are provided by Wiegert et al. (2015). In this work, we go a step further by looking at highly-inclined galaxies ($70^\circ \leq i \leq 78^\circ$) for which maps of the SFR surface density are available. Vollmer et al. (2020) predicted radio continuum maps by convolving the source map, represented by that of the SFR surface density, with Gaussian (diffusion) and exponential (streaming) kernels. Here, we add a vertical component to the predicted radio continuum maps, which is anchored in the star-forming disk. We would like to know if the halo radio continuum emission carries information on the underlying disk and if the radio continuum halo has a constant height or if it is flaring. Extending the CHANG-ES methodology, we use the spectral index (SI) of the halo emission to investigate if a halo is (i) advection or diffusion and (ii) escape or synchrotron loss-dominated.

This article is structured in the following way: the radio continuum data and the those used to calculate the star formation maps are presented in Sect. 2. Our analytical model for the 3D distribution of the radio continuum emissivity and its projection of the sky are explained in Sect. 3. The presentation of the results (Sect. 4) is followed by a classification of the radio halos (Sect. 5). We discuss our results in Sect. 6 and give our conclusions in Sect. 7.

2. Data

The integrated SFR, the radio continuum flux at 4.85 GHz from Vollmer et al. (2013), and the stellar mass from Boselli et al. (2015) of each galaxy are presented in Table 1.

2.1. Radio continuum

For the radio continuum maps we used published VLA data at 4.85 and 1.4 GHz at 15–22'' resolution for all galaxies. The Virgo spiral galaxies were observed at 4.85 GHz between October 12, 2009 and December 23, 2009 with the Very Large Array (VLA) of the National Radio Astronomy Observatory (NRAO) in the D array configuration. The bandwidths were 2×50 MHz. The final cleaned maps were convolved to a beam size of $22'' \times 22''$ (Vollmer et al. 2013). In addition, we observed the galaxies at 1.4 GHz on March 21, 2008 in the C array configuration. The bandwidths were 2×50 MHz. The final cleaned maps were convolved to a beam size of $22'' \times 22''$ (Vollmer et al. 2013). At a distance of 17 Mpc, $1''$ corresponds to 82 pc. Furthermore, we used the C-band D-array and L-band C-array data from CHANG-ES (Irwin et al. 2012). The C-band and L-band images of our galaxy sample are presented in Figs. A.1 and A.2. We used the 1.4 GHz data of NGC 4294 from VIVA (Chung et al. 2009) because these data significantly improved the model results.

For our analysis, we subtracted the thermal free-free radio emission according to the recipe of Murphy et al. (2008),

$$\left(\frac{S_{\text{therm}}}{\text{Jy}}\right) = 7.9 \times 10^{-3} \left(\frac{T}{10^4 \text{ K}}\right)^{0.45} \left(\frac{\nu}{\text{GHz}}\right)^{-0.1} \left(\frac{I_{\nu}(24 \mu\text{m})}{\text{Jy}}\right), \quad (1)$$

where T is the electron temperature, and $I_{\nu}(24 \mu\text{m})$ is the flux density at a wavelength of $24 \mu\text{m}$. We note that there are other alternative methods to account for the thermal free-free emission using, for example, the extinction-corrected $\text{H}\alpha$ emission (Tabatabaei et al. 2007, Heesen et al. 2014). Since information on the spatially resolved $\text{H}\beta$ lines was not available to us, we could not calculate the extinction correction of the $\text{H}\alpha$ emission based on the Balmer decrement.

2.2. Star formation rate

The SFR surface density was calculated from the FUV luminosities corrected by the total infrared to FUV luminosity ratio (Hao et al. 2011). This method takes into account the UV photons from young massive stars that escape the galaxy, and those which are absorbed by dust and re-radiated in the far infrared:

$$\dot{\Sigma}_* = 8.1 \times 10^{-2} (I(\text{FUV}) + 0.46 I(\text{TIR})), \quad (2)$$

where $I(\text{FUV})$ is the GALEX far ultraviolet and $I(\text{TIR})$ the total infrared intensity based on Spitzer IRAC and MIPS data in units of MJy sr^{-1} . $\dot{\Sigma}_*$ has the units of $\text{M}_{\odot} \text{kpc}^{-2} \text{yr}^{-1}$. This prescription only holds for a constant SFR surface density over the last few 100 Myr.

The deprojected star formation maps of our galaxy sample are presented in Fig. B.1. Since the deprojection is not unique, our deprojected maps do not look like typical face-on galaxies: spiral structures are patchy and the overall disk structure is more oval than round (especially for NGC 4419). Nevertheless, given the simplicity of our halo model, we are confident that the quality of our simple deprojection is good enough to constrain the major halo properties: its dependence on the morphology of the underlying starforming disk, the radial profile of the halo height, and the halo flux fraction.

3. Method

As in Vollmer et al. (2020), we convolved the star formation maps of the six highly-inclined galaxies with adaptive Gaussian smoothing kernels in two dimensions to obtain model radio continuum emission maps. These authors showed that the smoothing length scales depend on the observation frequency. For simplicity and in line with the results of Vollmer et al. (2020), we used a constant smoothing length scale of 2.0 kpc at 20 cm and 1.3 kpc at 6 cm. We did not vary these scale lengths because the models with different halo types were quite time-consuming.

If the radio halo is diffusion-dominated a Gaussian vertical profile is expected, where if the halo is advection dominated an exponential halo profile is expected. A thin and a thick disk give rise to two Gaussians or exponentials. We also used the empirical function of Oosterloo et al. (2007), which they fitted to the HI halo of NGC 891. For most of the models the height depends of the galactic radius R but it might also depend on the local SFR surface density $\dot{\Sigma}_*$. The specific intensity I_{ν} depends on $\dot{\Sigma}_*$ in most of the models but it may also depend on R . We also allow for a small offset o of the vertical profiles. In this way, we can correct for possible small errors of the position angle and warps of the galactic disk. In general, the offset was found to be $o \lesssim 300$ pc.

In total, we used 10 different halo prescriptions (Table 2). It is expected that the CRe follow the vertical halo magnetic field when they leave the thin galactic disk. By applying our vertical halo profiles, we implicitly assume that the halo magnetic fields are vertical without any bending (see Heald et al. 2022 for a more sophisticated model). For the production of the model radio continuum map the following steps were performed: (i) insertion of the SFR surface density map as the thin disk into a model cube, (ii) convolution with a Gaussian to generate the predicted radio continuum map of the thin disk, (iii) addition of the halo, (iv) projection according to the inclination and position angle of the galaxy, and (v) convolution with a Gaussian to obtain the spatial resolution of the observations. Our models have up to 12 variables, which have to be determined by fitting the model to the radio continuum map. For each model the reduced $\chi^2 = \sqrt{1/N \sum_i (f_{\text{obs}} - f_{\text{model}})^2}$ was calculated using the rms of the radio continuum map, where f_{obs} and f_{model} are the observed and model flux densities, respectively.

For the fitting of the models to the data, we performed a multidimensional minimization using the downhill simplex method (Nelder & Mead 1965). The IDL routine *amoeba* (Press et al. 1992) was used for this purpose. We checked for a very limited number of cases that different initial conditions lead to the same results. However, we cannot exclude that a local minimum was found by *amoeba*. All models converged to the presented solutions. The emission of the four quadrants of the radio continuum maps were fitted separately. Since NGC 4192 harbors a strong central point source associate to an active galactic nu-

Table 1. Galaxy sample

	D (Mpc)	i (deg)	$S_{4.85 \text{ GHz}}$ (mJy)	$f_{4.85 \text{ GHz}}^{\text{therm}}$	$S_{1.4 \text{ GHz}}$ (mJy)	$f_{1.4 \text{ GHz}}^{\text{therm}}$	SI	$D_{4.85 \text{ GHz}}$ (kpc)	SFR ($M_{\odot} \text{yr}^{-1}$)	$\log(M_*)$ ($M_{\odot}$)
NGC4178	17	70	13.0	0.07	30.7	0.04	-0.69	23.5	0.8	9.6
NGC4192	17	78	35.0	0.21	120.9	0.06	-1.00	30.5	1.8	10.7
NGC4294	17	70	11.5	0.17	32.3	0.09	-0.83	12.8	0.5	9.2
NGC4419	17	74	23.6	0.32	59.8	0.14	-0.74	10.7	1.4	10.2
NGC4532	17	70	51.2	0.11	119.9	0.06	-0.68	15.2	1.3	9.2
NGC4808	17	68	19.4	0.22	62.6	0.08	-0.94	13.2	0.9	9.5

Table 2. Radio continuum halo prescriptions.

gauss	$h_1 = x_2 + x_3 R^{x_4}$ $h_2 = x_5 + x_6 \sum_{*}^{x_7}$	$o = x_8 + x_9 R^{x_{10}}$	$I_v = x_{11} \sum_{*}^{x_{12}} \exp(-(z - o /h_1)^2) +$ $x_0 \sum_{*}^{x_1} \exp(-(z - o /h_2)^2)$
gausssinh	$h_1 = x_2 + x_3 R^{x_4}$ $h_2 = x_5 + x_6 \sum_{*}^{x_7}$	$o = x_8 + x_9 R^{x_{10}}$	$I_v = x_{11} \sum_{*}^{x_{12}} \exp(-(z - o /h_1)^2) +$ $x_0 \sum_{*}^{x_1} \sinh(- z - o /h_2)/(\cosh(- z - o /h_2))^2$
exp	$h_1 = x_2 + x_3 R^{x_4}$ $h_2 = x_5 + x_6 \sum_{*}^{x_7}$	$o = x_8 + x_9 R^{x_{10}}$	$I_v = x_{11} \sum_{*}^{x_{12}} \exp(- z - o /h_1) +$ $x_0 \sum_{*}^{x_1} \exp(-(z - o /h_2))$
expsinh	$h_1 = x_2 + x_3 R^{x_4}$ $h_2 = x_5 + x_6 \sum_{*}^{x_7}$	$o = x_8 + x_9 R^{x_{10}}$	$I_v = x_{11} \sum_{*}^{x_{12}} \exp(- z - o /h_1) +$ $x_0 \sum_{*}^{x_1} \sinh(-(z - o /h_2))/(\cosh(- z - o /h_2))^2$
onegauss	$h = x_2 + x_3 R^{x_4}$	$o = x_5 + x_6 R^{x_7}$	$I_v = x_0 \sum_{*}^{x_1} \exp(-(z - o /h)^2)$
oneexp	$h = x_2 + x_3 R^{x_4}$	$o = x_5 + x_6 R^{x_7}$	$I_v = x_0 \sum_{*}^{x_1} \exp(- z - o /h)$
gauss sfr	$h = x_2 + x_3 \sum_{*}^{x_4}$	$o = x_5 + x_6 R^{x_7}$	$I_v = x_0 \sum_{*}^{x_1} \exp(-(z - o /h)^2)$
exp sfr	$h = x_2 + x_3 \sum_{*}^{x_4}$	$o = x_5 + x_6 R^{x_7}$	$I_v = x_0 \sum_{*}^{x_1} \exp(- z - o /h)$
onegauss smooth	$h = x_2 + x_3 R^{x_4}$	$o = x_5 + x_6 R^{x_7}$	$I_v = x_0 R^{x_1} \exp(-(z - o /h)^2)$
oneexp smooth	$h = x_2 + x_3 R^{x_4}$	$o = x_5 + x_6 R^{x_7}$	$I_v = x_0 R^{x_1} \exp(- z - o /h)$

cleus, the model was not fitted to the data in a band around the center (Fig. 1). Each model needed about two days on a single CPU to converge.

We realized that for models, where we tried to fit the thin disk with a separate profile (gauss, gausssinh, exp, expsinh in Table 2), the fluxes were sometimes distributed between the two profiles in an arbitrary way. Therefore, we did not use the scaleheights h , h_1 , and h_2 but determined an effective halo height H . For each galactic radius R we calculated H with

$$\int_0^H I_v dz = 0.5 \int_0^{z_{\max}} I_v dz, \quad (3)$$

where $z_{\max} = 8.2$ kpc. For NGC 4178, we realized that the fitting procedure lead to much larger or smaller effective heights than the mean height. We thus decided to discard these solutions by applying `resistant_mean` in IDL to identify the outlying solutions. These are marked with parentheses in Table C.1.

The final radial profile of H were calculated (i) with all 10 models and (ii) with the four best-fitting models. Furthermore, we calculated the thin disk and halo flux fraction for each model to determine the spectral index (SI) of the halo emission.

Our rather time-consuming model calculations did not permit a proper estimation of the uncertainties of the different parameters via Markov Chain Monte Carlo (MCMC) techniques. Instead, we investigated which parameter has the strongest influence on the reduced χ^2 . We did this by decreasing and increasing each parameter separately by 50 % for the NGC 4192 models at 6 cm. We then identified the parameters, which increased the reduced χ^2 by at least a factor of two. As expected, the reduced χ^2 is sensitive to the exponents of the radius in the descriptions of the height and the vertical offset. In addition, the constant of the

vertical offset and the exponent of the SFR surface density also have a significant influence on the reduced χ^2 . We conclude that all exponents in the prescriptions of Table 2 are well constrained.

4. Results

We found $10 \lesssim \chi^2 \lesssim 50$ for most of the models of NGC 4178, NGC 4192, NGC 4294, and NGC 4808 (Tables C.1, C.2, C.4, and C.7). For NGC 4192CHANG-ES, the range is $10 \lesssim \chi^2 \lesssim 100$ (Table C.3), for NGC 4419 it is $100 \lesssim \chi^2 \lesssim 800$ (Table C.5), and for NGC 4532 it is $30 \lesssim \chi^2 \lesssim 400$ (Table C.6). Thus, the models reproduce the radio emission distribution of NGC 4419 and NGC 4532 significantly less well than that of the other galaxies. We note that the reduced χ^2 of the smoothing experiments of Vollmer et al. (2020) were of the same order.

When we compared the three models with the lowest χ^2 at the two wavelengths for a given quadrant in a given galaxy, we did not find preferences for a Gaussian (diffusion) or exponential (advection) vertical profile (Tables C.1 to C.7). As for the transport of CRE within the galactic disk studied in Vollmer et al. (2020), it is not possible to discriminate between diffusion- and advection-dominated radio continuum halos solely based on the type of the vertical intensity profile.

The vertical profiles, which exclusively depend on the galactic radius R (onegauss smooth and oneexp smooth; Table 2), are very rarely found amongst the three models with the lowest χ^2 (Tables C.1 to C.7). When this is the case, it is found at one wavelength but not in the other. We thus conclude that overall the halo emission contains information on the underlying distribution of the SFR surface density ($\dot{\Sigma}_*$).

The surface brightness profiles along the major axis and along lines parallel to the minor axis for NGC 4192 based on our and the CHANG-ES 20 cm and 6 cm data together with the residual maps are shown in Figs. 1 and C.1. The best-fit models were selected in all four quadrants separately.

As expected, we found consistent overall results for the CHANG-ES and our data. However, the details of the residual maps are different. For example, the negative residuals in the eastern half of the galactic disk based on the CHANG-ES data are not present in the residual maps based on our data. Halo radio continuum emission is clearly detected in all quadrants (dashed lines, which correspond to models with halo emission, compared to the dotted lines, which correspond to models without halo emission). The halo emission also improves the profile along the major axis. The halo emission is less prominent at 6 cm than at 20 cm. The residuals are larger on the western side of the galactic disk than on the eastern side.

The radial profiles of the halo effective height H of NGC 4192 are presented in Fig. 2 for the four best models and in Fig. D.1 for all ten models. The height profiles derived from the CHANG-ES and our data are in good agreement with each other. The radio halo emission of all quadrants is flaring. The western half of the disk is somewhat thicker than the eastern half at both wavelengths. Overall, the radially averaged halo heights and halo flux fractions based on the CHANG-ES and our data are consistent (Table 3). Our model procedure is thus robust.

NGC 4178 is the only galaxies in our sample, which does not show detectable radio halo emission at 6 cm (Table 3 and Figs. 3 and D.2). The mean effective height is small (~ 100 pc) at 6 cm. At 20 cm the halo emission distribution has a effective height of ~ 300 pc. NGC 4294 and NGC 4419 have relatively thin radio continuum halos (300-400 pc at both wavelengths). The halo flux fraction of NGC 4419 ($f > 0.7$) is significantly higher than that of NGC 4294 ($f \sim 0.5$). In NGC 4419 we detect somewhat detached extended 6 cm emission at very low surface brightnesses, which cannot be properly reproduced by our models (Figs. 3 and D.2). NGC 4532 has a thick ($H \sim 0.7$ kpc at 6 cm and $H \sim 1.8$ kpc at 20 cm) but not prominent radio continuum halo ($f \sim 0.3$) at both wavelengths (Figs. 3 and D.2). NGC 4808 has the thickest and prominent radio continuum halo ($H \sim 0.8$ kpc at 6 cm and $H \sim 2.0$ kpc at 20 cm; Figs. 4 and D.3).

The majority of our galaxies show flaring radio continuum halos meaning that the effective height increases with galactic radius (Figs. 2 to 4 and Fig. D.1 to D.3). In most of the cases the radial profiles of the effective height have different behaviors in the four quadrants. There can be an east-west asymmetry (NGC 4178, NGC 4192) or a north-south asymmetry (NGC 4532).

The radially averaged effective heights as a function of the size of the radio continuum disk for our highly-inclined Virgo spiral galaxies are compared to those of the CHANG-ES galaxies in Fig. 5. Except for NGC 4178, our Virgo galaxies follow the trend of increasing effective height with increasing radio continuum size found by the CHANG-ES collaboration (Krause et al. 2018). Moreover, the effective heights of NGC 4532 and NGC 4808 at 20 cm are significantly larger than expected from the correlation. As already stated before, a radio continuum halo is absent at 6 cm in NGC 4178 and it is very thin at 20 cm given its large radio continuum size.

5. The classification of radio continuum halos

The vertical intensity profile of a radio continuum halo is determined by the transport model, which can be diffusion, streaming, or advection, and the decrease of synchrotron emission, which can be due to synchrotron losses or CRe escape. The ratio r_H between the effective halo heights at 6 and 20 cm and the SI of the halo are different for different types of halos. As stated by Krause et al. (2018), in a synchrotron energy loss-dominated halo the outer halo boundary is determined where the CRe have lost their energy by a sufficient amount that its radiation is below the observational detection limit. In an escape-dominated halo the halo boundary is observed where the number of CRe and the magnetic field strength are too small to emit detectable radio emission, which is also dependent on the sensitivity of the observations. In practice both processes can occur simultaneously along the line of sight.

We followed Krause et al. (2018) and Heesen (2021) for the height ratios. Based on the height ratio a diffusion synchrotron loss-dominated halo cannot be distinguished from an advection escape-dominated halo ($r_H \sim 1$). We suggest to break this degeneracy by including the spectral index (SI) into the analysis: whereas the SI for synchrotron losses is about -1.0 , it is ~ -0.5 if escape-losses dominate the halo. Additional CRe aging is taken into account by a slight steepening of the radio continuum spectrum (SI decreased by -0.25). We found the following halo characteristics: (i) synchrotron loss-dominated with advection: $r_H \sim 1.9$, $SI \sim -1.25$; (ii) synchrotron loss-dominated with diffusion: $r_H \sim 1.2$, $SI \sim -1.25$; (iii) escape-dominated with diffusion: $r_H \sim 1.1$, $SI \sim -0.75$, and (iv) escape-dominated with advection: $r_H \sim 1.1$, $SI \sim -0.75$. The two escape-dominated halo types (iii) and (iv) are indistinguishable. It is expected that the preferred CRe transport mechanism for escape-dominated halos is advection by a galactic wind or outflow provided that the SFR surface density is equal to or higher than the average of star-forming galaxies. Since galaxies with lower SFR surface density (green valley galaxies) are rare, most of the escape-dominated halos should be dominated by advection rather than by diffusion. We arbitrarily draw circles around these points to delimit the different regions if the r_H -SI diagram of Fig. 6. Cosmic ray transport models for a synchrotron-loss dominated halo with diffusion and halos with advection calculated with SPINNAKER (Heesen et al. 2018) are consistent with our choice of the three regions in SI-h20/h6 space.

The CHANG-ES galaxies for which the height ratios and halo SI are measured are NGC 4013 (Stein et al. 2019a), NGC 4217 (Stein et al. 2020), and NGC 4666 (Stein et al. 2019b). Whereas diffusion is the CRe transport mechanism in NGC 4013 (Gaussian vertical profile), it is advection in the other two galaxies (exponential vertical profile). Indeed, NGC 4013 lies within the region of diffusion synchrotron loss-dominated halos whereas NGC 4217 and NGC 4666 lies at the edge but still within the region of advection escape-dominated halos. This demonstrates that our halo classification based on r_H and SI is meaningful.

The halo SI roughly follow the SI of the integrated emission. The mean deviation of the halo SI from the integrated SI is 0.12. As expected, most halo SI (5 out of 7) are somewhat lower (steeper) than the integrated SI.

The corresponding halo classification for NGC 4192 is presented in Fig. 7 based on the CHANG-ES and our data for all ten models and the four best models. All results are in good agreement with each other. The uncertainties are large but not

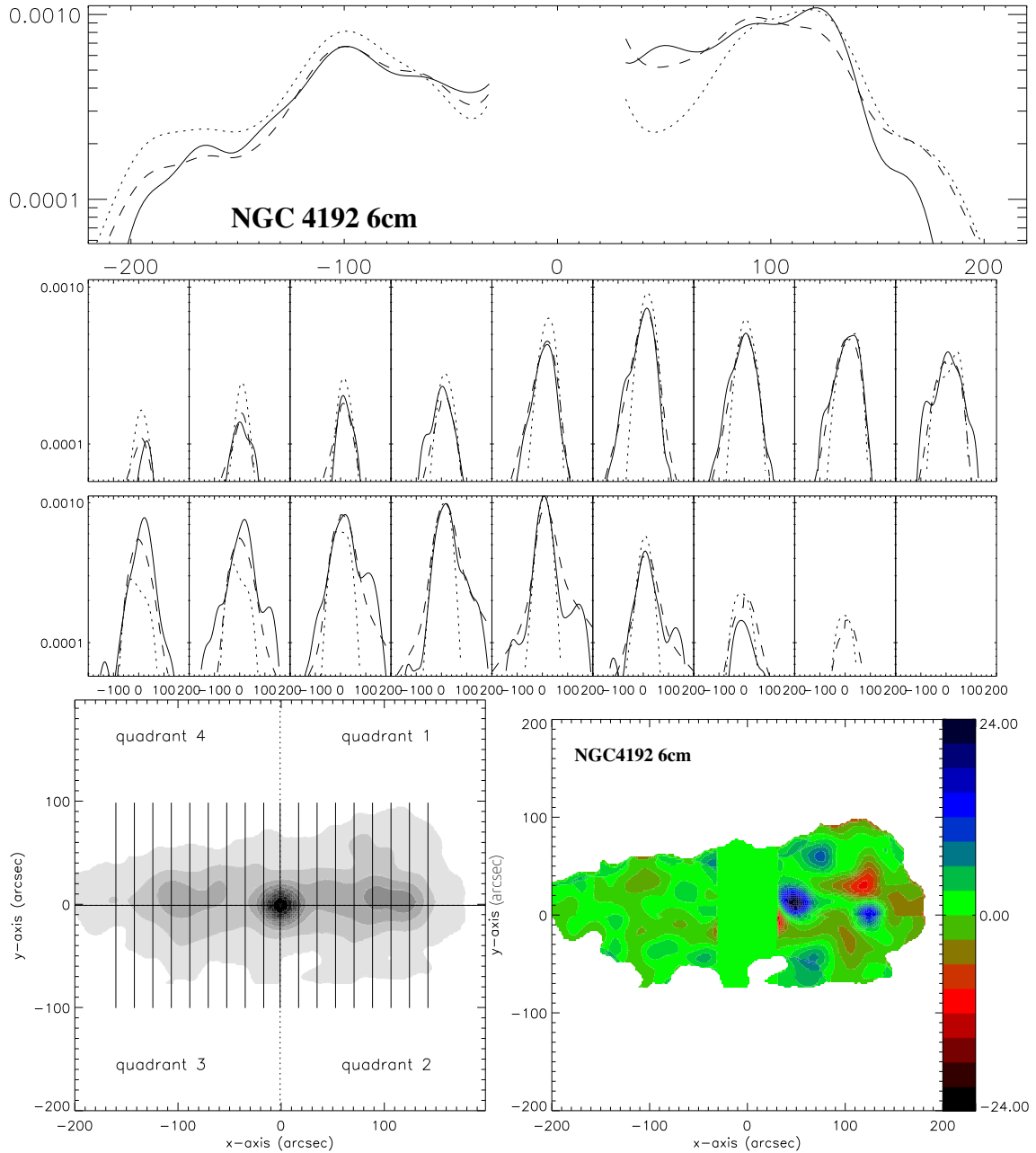


Fig. 1. Radio continuum halo model of NGC 4192. Upper panel: profiles along the minor and major axes. Solid lines: observations, dashed lines: model including a thin disk and a halo, dotted lines: model including only a thin disk. All distance are in arcseconds. Lower left panel: locations of the slices along the major and minor axis. Lower right panel: maps of the model residuals in units of the rms.

too large to permit the classification of the halo, which is advection escape-dominated in NGC 4192.

The radio halo of NGC 4294 is also most probably advection escape-dominated (Fig. 9). Only the third quadrant is consistent with being diffusion synchrotron-dominated. Given that a vertical halo magnetic field is observed in this quadrant (Vollmer et al. 2013), we think that the halo of this quadrant is also advection escape-dominated (see also Sect. 6).

For the other Virgo galaxies the classification is less clear. When the halo height ratios of a given quadrant is very high, it is not shown in the corresponding r_H -SI diagram. In NGC 4178 the height ratio in the second quadrant is ~ 8 because of a large height at 20 cm. Whereas the halo of the third quadrant is advection escape-dominated, the conclusions for the first and fourth quadrants are less clear (Fig. 8). The halos of the latter quad-

rants are marginally consistent with being advection escape-dominated within the error bars.

In NGC 4419 the halos of all four quadrants are broadly consistent with being advection escape-dominated (lower panel of Fig. 10). In NGC 4532 the radio continuum halos of all four quadrants are consistent with being advection escape-dominated or diffusion synchrotron loss-dominated, with a preference for the former (lower panel of Fig. 11). The halos of the first and second quadrants in NGC 4808 lie between the regions of advection escape and advection synchrotron dominance (lower panel of Fig. 12). The halo of the fourth quadrant is probably advection escape-dominated whereas the classification of the halo in the third quadrant is uncertain. We conclude that, overall, advection escape-dominated radio continuum halos prevail in our sample.

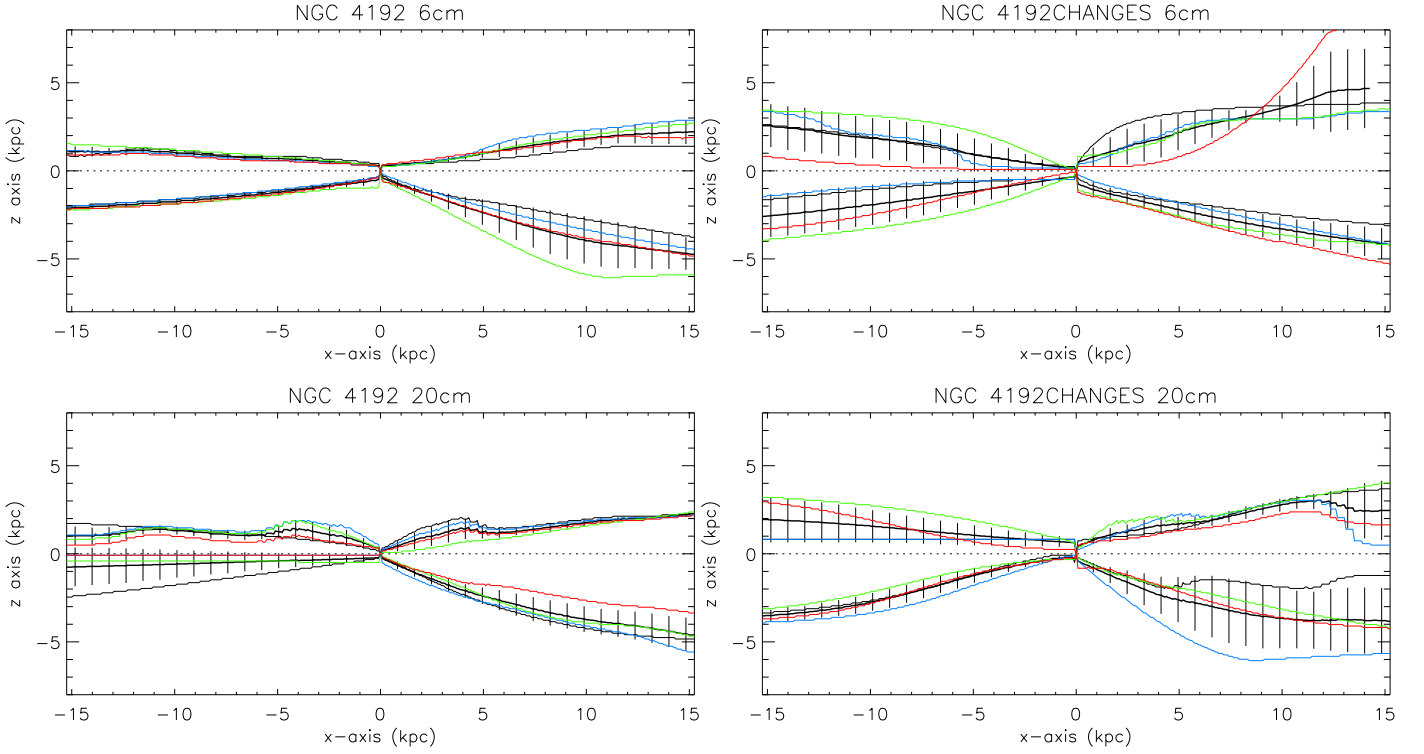


Fig. 2. Radial profiles of the halo scale height of NGC 4192. Upper panel: all ten models. Lower panel: best four models. Models with a low χ^2 are red, those with a high χ^2 are blue.

Table 3. Mean heights and flux fractions.

	$h_{\text{all}}^{6\text{cm}}$ (kpc)	$f_{\text{all}}^{6\text{cm}}$	$h_{4\text{ best}}^{6\text{cm}}$ (kpc)	$f_{4\text{ best}}^{6\text{cm}}$	$h_{\text{all}}^{20\text{cm}}$ (kpc)	$f_{\text{all}}^{20\text{cm}}$	$h_{4\text{ best}}^{20\text{cm}}$ (kpc)	$f_{4\text{ best}}^{20\text{cm}}$
N4178 disk	0.10 ± 0.03	0.58 ± 0.13	0.09 ± 0.02	0.61 ± 0.17	0.30 ± 0.24	0.62 ± 0.17	0.25 ± 0.22	0.65 ± 0.19
N4192 halo	1.59 ± 1.03	0.60 ± 0.25	1.73 ± 0.98	0.61 ± 0.18	1.40 ± 1.19	0.53 ± 0.25	1.55 ± 1.05	0.55 ± 0.14
N4192C halo	1.78 ± 1.02	0.62 ± 0.23	2.19 ± 0.92	0.52 ± 0.14	1.41 ± 1.19	0.50 ± 0.17	2.11 ± 0.93	0.62 ± 0.14
N4294 halo	0.37 ± 0.15	0.55 ± 0.33	0.40 ± 0.17	0.47 ± 0.32	0.41 ± 0.14	0.55 ± 0.35	0.41 ± 0.17	0.56 ± 0.31
N4419 halo	0.33 ± 0.79	0.86 ± 0.40	0.67 ± 1.19	0.92 ± 0.35	0.30 ± 0.90	0.75 ± 0.16	0.29 ± 0.45	0.76 ± 0.12
N4532 halo	0.65 ± 0.91	0.20 ± 0.20	1.13 ± 1.29	0.30 ± 0.22	1.89 ± 1.85	0.30 ± 0.18	1.81 ± 1.56	0.38 ± 0.16
N4808 halo	0.90 ± 1.00	0.66 ± 0.21	0.79 ± 0.57	0.66 ± 0.20	2.29 ± 1.56	0.62 ± 0.28	1.82 ± 0.95	0.71 ± 0.19

The mean height ratios as a function of the mean halo SI for our Virgo galaxies are shown in Fig. 6. Based on the mean values the halos of NGC 4192, NGC 4294, and NGC 4419 are advection escape-dominated. Despite its large error bar for the height ratio, the halo of NGC 4178 is most probably advection/synchrotron escape-dominated. The halos of NGC 4532 and NGC 4808 have rather large error bars in both direction, which prevent their classification based on the r_H -SI diagram.

6. Discussion

Radio continuum halo can represent a significant fraction of the total radio continuum emission of a starforming spiral galaxy. At 20 cm and 6 cm between 30 and 70 % of the total radio continuum emission originate in the halo (Table 3; Stein et al. 2019a; Stein et al. 2020). The fraction is higher at low frequencies. This is in line with the results of radio continuum model of Vollmer et al. (2022, 2025) where the effective height of the radio continuum emission is that of the gas disk (H) and not that of the starforming disk (l_{driv} in their nomenclature).

All galaxies of our sample are located in the Virgo cluster (see Fig. 1 of Vollmer et al. 2013). NGC 4402 and NGC 4330 show strongly asymmetric radio continuum halos, where one side is compressed by ram pressure from the intercluster medium and the other side is linked to stripped material (Crowl et al. 2005, Vollmer et al. 2013). The radio continuum halos of NGC 4294, NGC 4532, and NGC 4808 show a lesser degree of asymmetry. All three galaxies are not H I-deficient (Chung et al. 2009). NGC 4294 is part of a galaxy pair and has an asymmetric outer H I distribution. NGC 4532 and NGC 4808 have extended asymmetric H I envelopes (Chung et al. 2009). It thus seems that the cluster environment can lead to strongly asymmetric radio continuum halos via ram pressure, whereas the local environment (galaxy pairs or external gas accretion) leads to rather weakly asymmetries of the halos.

The ratio between the radio luminosity and the SFR is normal for all galaxies except NGC 4532, for which it is twice as high as the mean (Fig. 1 of Vollmer et al. 2020 and Table 1). On the other hand, the mean 6 cm surface brightness of NGC 4532 and NGC 4808 is about five times higher than that of NGC 4178.

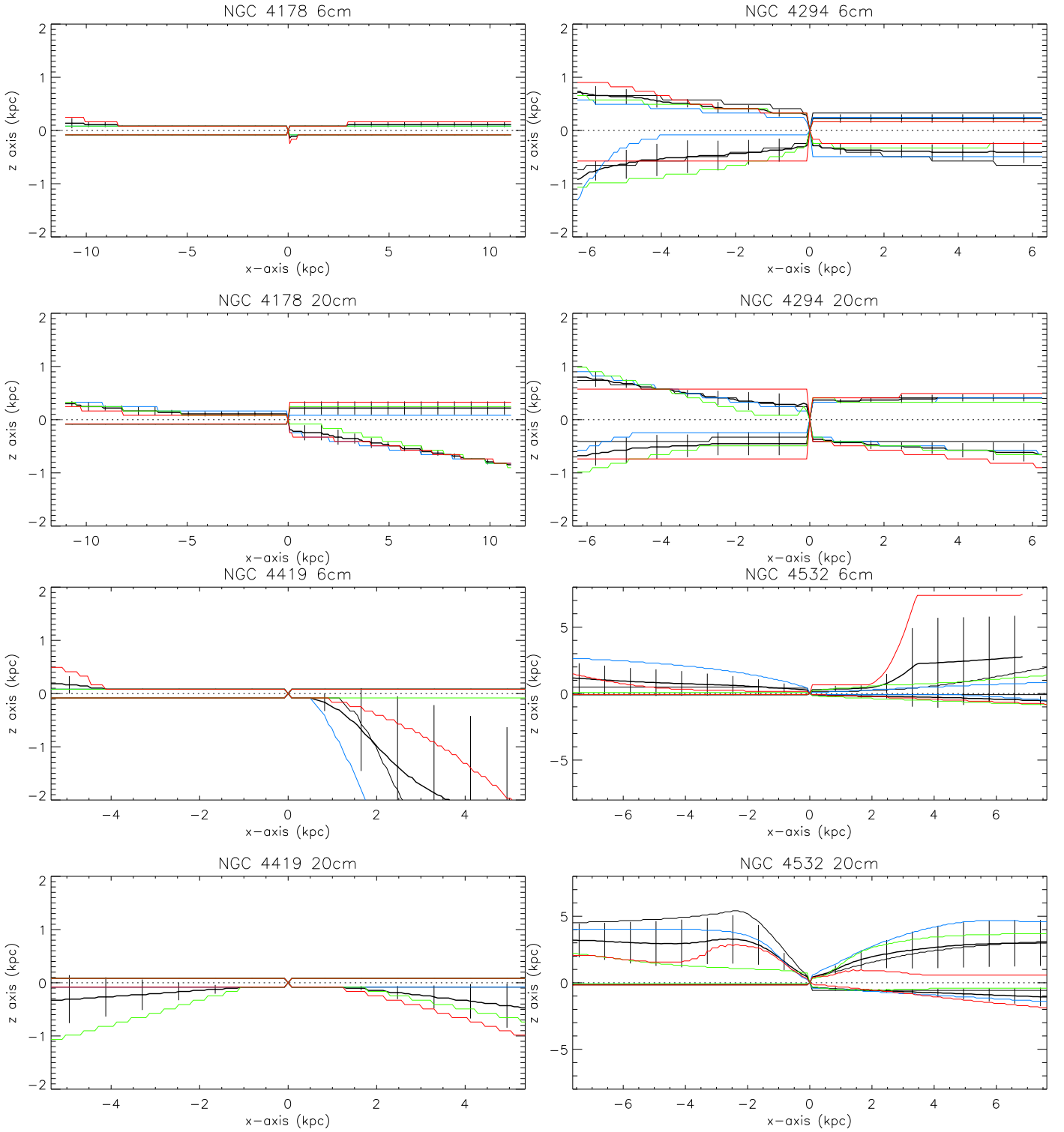


Fig. 3. Radial profiles of the halo scale height of NGC 4178, NGC 4294, NGC 4419, NGC 4532. Best four models. Models with a low χ^2 are red, those with a high χ^2 are blue.

The mean 6 cm surface brightnesses of NGC 4192, NGC 4294, and NGC 4419 lie between these two extremes (Vollmer et al. 2013). We conclude that NGC 4532 and NGC 4808 most probably drive galactic winds and their halos are caused by CRe advection.

It turned out that the estimation of the halo parameters is best for large galaxies with a relatively high radio surface brightness (NGC 4192), which is expected. For the halos of the other galax-

ies we can use additional information from large-scale magnetic field structure derived from the polarized 6 cm radio continuum emission (Fig. D.4). The large-scale magnetic field configuration of a disk galaxy can be divided into three main types: (i) disk type, where the large-scale magnetic field is parallel to the disk plane, (ii) disk-halo type, which shows a characteristic X-structure, (ii) halo type, where the large-scale magnetic field is perpendicular to the disk plane (see, e.g., Irwin et al. 2024).

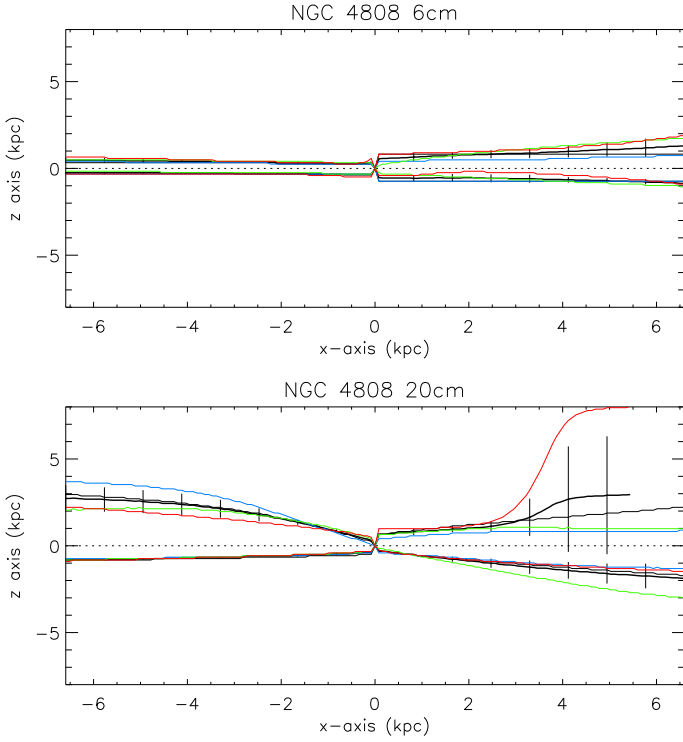


Fig. 4. Radial profiles of the halo scale height of NGC 4808. Best four models. Models with a low χ^2 are red, those with a high χ^2 are blue.

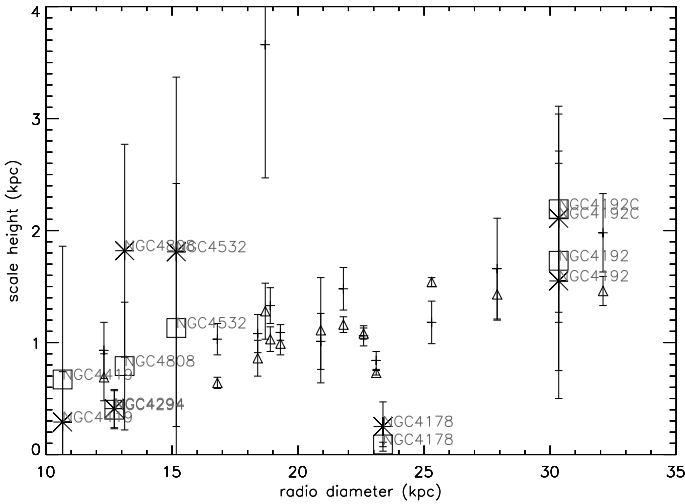


Fig. 5. Halo scale heights as function of the radio diameter. Triangles: CHANG-ES galaxies at 6 cm, pluses: CHANG-ES galaxies at 20 cm, boxes: Virgo galaxies at 6 cm, asterisks: Virgo galaxies at 20 cm.

The projected magnetic field lines is of disk-halo type in NGC 4192 and NGC 4419, of halo type in the southwestern disk of NGC 4294, of disk-halo and halo type in NGC 4532, and of halo type in NGC 4808. We interpret the vertical structures of the large-scale magnetic field within the disk-halo and halo types as a sign of a galactic outflow or wind. As expected, the two galaxies with the highest radio continuum surface brightnesses and thus SFR surface density show clear signs of galactic winds. These outflows lead to an enhanced radio continuum emission with respect to the SFR only in NGC 4532, which has the highest specific SFR of our galaxy sample ($\text{sSFR} = 8.2 \times 10^{-10} \text{ yr}^{-1}$) and might be qualified as a starburst. Thus, all galaxies except NGC 4178 are expected to harbor an advection-dominated halo.

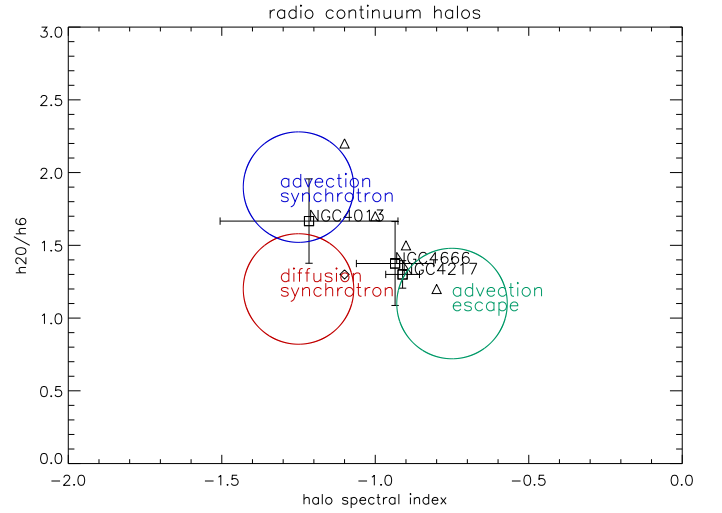


Fig. 6. CHANG-ES galaxies: height ratio at 20cm and 6cm as a function of the spectral index between 20cm and 6cm. Triangles: SPINNAKER models of halos with advection. Diamond: SPINNAKER model of a synchrotron-loss dominated halo with diffusion.

This in turn means that our estimate of the SI is more robust than that of the height ratio (see Sect. 5).

All halos of our highly-inclined galaxy sample contain information on the underlying star formation distribution within the galactic disk (see Sect. 4). This is expected in an advection-dominated halo, where the CRE are transported into the halo by a galactic wind or outflow. As for the CHANG-ES sample, our galaxy sample is also dominated by advection escape-dominated radio continuum halos.

The particularly thin radio disk or halo of NGC 4178 (Fig. 5) is remarkable. Vollmer et al. (2013) did not detect any polarized 6 cm radio emission in this galaxy. This thinness calls for an explanation. Another Virgo galaxy in the sample of Vollmer et al. (2013) is NGC 4216. It has the lowest 6 cm mean surface brightness of the sample, a factor of 2.5 lower than that of NGC 4192 and a factor of 1.7 lower than that of NGC 4178. Whereas NGC 4216 is strongly H I deficient, NGC 4178 is not. In addition, NGC 4178 has a normal specific SFR of $\text{sSFR} = 2 \times 10^{-10} \text{ yr}^{-1}$. The radio-thinness is not due to a diffusion synchrotron loss-dominated halo because the ratio between the 6 cm vertical height and diameter are about the same for NGC 4013, which has a diffusion synchrotron loss-dominated halo, and NGC 4217, which has an advection escape dominated halo. It thus appears that radio-thinness only correlates with the mean 6 cm surface brightness and the lack of significant polarized radio continuum emission. We can only speculate that NGC 4216 and NGC 4178 lack a strong halo magnetic field. In this case, the halo is probably diffusion escape-dominated because the SFR surface density is low compared to the average SFR surface density of starforming galaxies in both galaxies.

We can try to connect our flaring radio continuum disks to galactic H I an extended diffuse ionized gas (eDIG) disks. The H I radial profiles appear to have a typical shape, with the flaring increasing linearly with radius where the stellar disk dominates the local gravitational potential, and steepening to an exponential profile in the outer disk where the potential is probably dominated by the halo (O’Brien et al. 2010). Our radio continuum halos reside within the optical disk where stellar disk dominates the local gravitational potential. One might qualify the inner parts of the thick halos as linearly flaring but most of them flatten at larger radii. The latter behavior is contrary to that of the H I disk.

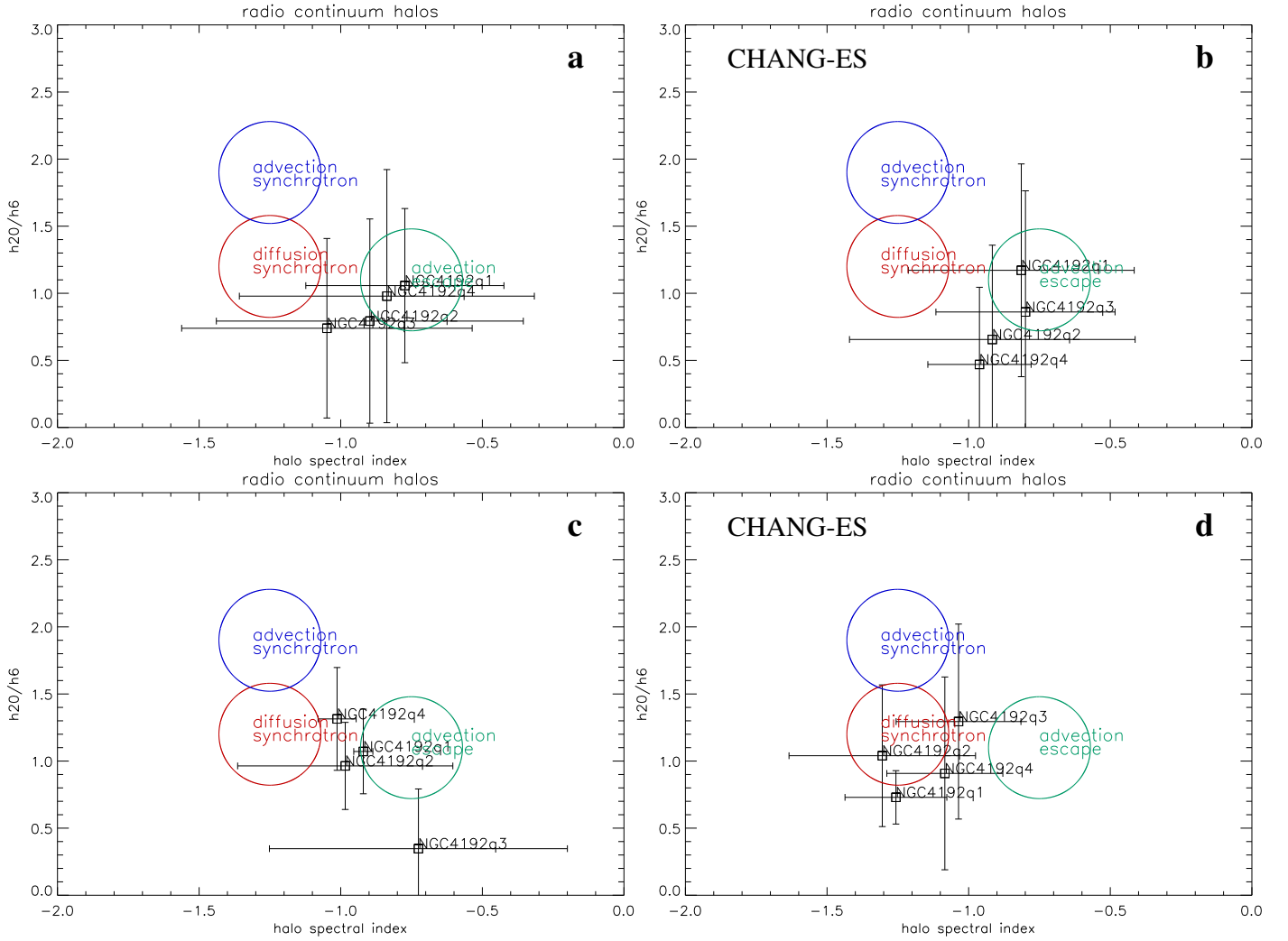


Fig. 7. NGC 4192. Height ratio as a function of the spectral index between 20cm and 6cm; (a,b) mean of all ten models, (c,d) mean of the four best-fit models.

We thus conclude that the exponential vertical H α profile at large galactic radii has a different cause than that of the flattening vertical radio continuum profile. Whereas the latter is caused by star formation and CRe transport, the latter is most probably caused by external gas accretion.

Concerning the warm ionized gas, Lu et al. (2023) found that the eDIG scale height of 22 nearby edge-on spiral galaxies is comparable to that at 20 cm. In addition, the eDIG is slightly more extended than the neutral gas. However, they did not measure radial profiles of the H α scale height. It will be interesting to compare the vertical profiles at large galactic radii of the three different gas phases. Clustered star formation might be a key ingredient to explain the multi-phase nature of the halo gas. Indeed, the injection spectrum of CRe and CRp of the model of Vollmer et al. (2024), which is needed to explain the integrated radio continuum emission of local and high- z main sequence and starburst galaxies, is that expected for superbubbles created by multiple SN remnants (Vieu et al. 2022). Multiple holes, bubbles, worms (Heiles 1984) and chimneys created by the explosions of multiple clustered SN allow the CRe to travel into the halo region. At the same time, the illuminated walls of these structures constitute the warm ionized medium or DIG as. This scenario was already proposed by Koo et al. (1992) and is

corroborated by more recent work, as for example, Belfiore et al. (2022).

7. Conclusions

The vertically extended component of the diffuse radio continuum can represent an important fraction of the total radio continuum emission of a starforming galaxy. The characteristics of radio continuum halos are traditionally measured in edge-on galaxies (Krause et al. 2018). These measurements are limited by the projection of the vertical emission distribution and by the assumption of a constant halo scale height. We made an attempt to reconstruct the radial properties of radio continuum halos in nearly edge-on galaxies ($70^\circ \leq i \leq 78^\circ$) where the SFR surface density distribution can still be deprojected and the vertical radio continuum emission is still well distinct from the disk emission. The deprojected SFR surface density distribution is convolved with a Gaussian kernel to take CRe diffusion within the galactic disk into account and a vertical profile of the radio continuum emissivity (Table 2) is added to the disk emission. The three dimensional emission distribution is then projected on the sky and compared to VLA radio continuum observations at 20 and 6 cm (Vollmer et al 2013). We also used publicly available VLA data from the CHANG-ES project (Irwin et al. 2012). The compari-

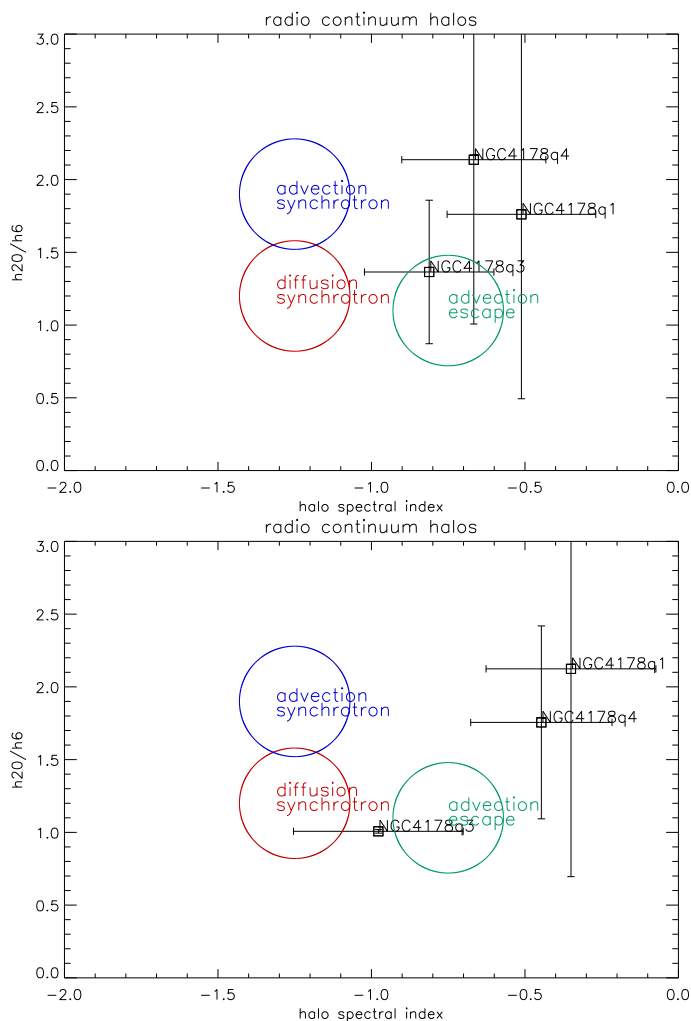


Fig. 8. NGC 4178. Height ratio as a function of the spectral index between 20cm and 6cm; upper panel: mean of all ten models; lower panel: mean of the four best-fit models.

son is made separately in the four quadrants of the radio continuum images. Our results are based on the 10 and 4 model with the lowest χ^2 . Based on the detailed comparison we conclude that

1. our method is robust because of the consistent overall results for the CHANG-ES and our data of NGC 4192;
2. overall the halo emission contains information on the underlying distribution of the SFR surface density;
3. the majority of our galaxies show flaring radio continuum halos;
4. except for NGC 4178, our Virgo galaxies follow the trend of increasing effective height with increasing radio continuum size found by the CHANG-ES collaboration (Krause et al. 2018);
5. radio continuum halos can represent a significant fraction of the total radio continuum emission of a starforming spiral galaxy. At 20 cm and 6 cm between 30 and 70 % of the total radio continuum emission originate in the halo (Table 3; Stein et al. 2019a; Stein et al. 2020);
6. a halo classification based on the height ratio and SI between 20 and 6 cm is proposed;
7. if we interpret the vertical structures of the large-scale magnetic field within the disk-halo and halo types as a sign of a galactic outflow or wind, all galaxies except NGC 4178 most probably harbor an advection dominated halo.

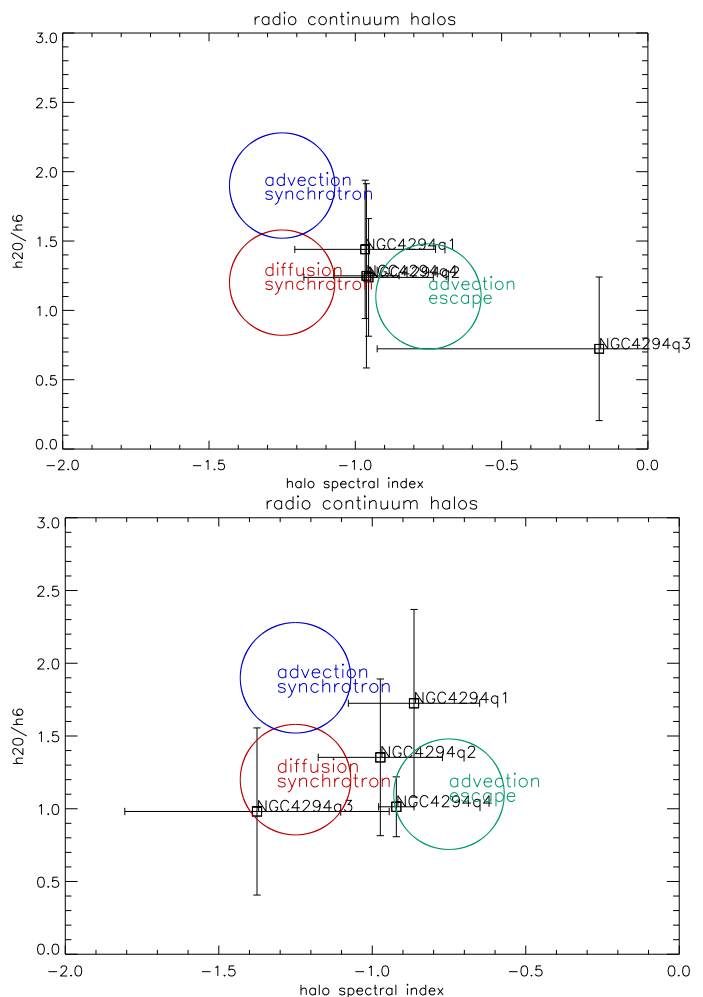


Fig. 9. NGC 4294. Height ratio as a function of the spectral index between 20cm and 6cm; upper panel: mean of all ten models; lower panel: mean of the four best-fit models.

The exponential vertical H_I profile at large galactic radii has a different cause than that of the flattening vertical radio continuum profile. Whereas the latter is caused by star formation and CRe transport, the latter is most probably caused by external gas accretion. Clustered star formation might be a key ingredient to explain the multi-phase nature of the halo gas. Multiple holes, bubbles, worms (Heiles 1984) and chimneys created by the explosions of multiple clustered SN allow the CRe to travel into the halo region. At the same time, the illuminated walls of these structures constitute the warm ionized medium or DIG. It will be interesting to compare the radial profiles of the energy densities of the warm neutral gas (H_I), the diffuse ionized gas or warm ionized medium, and the cosmic rays to investigate if and where the CRe can drive a galactic wind or outflow.

8. Data availability

Appendix C can be found on Zenodo (<https://doi.org/10.5281/zenodo.17258433>).

Acknowledgements. We would like to thank the CHANG-ES collaboration for providing the VLA data of NGC 4192.

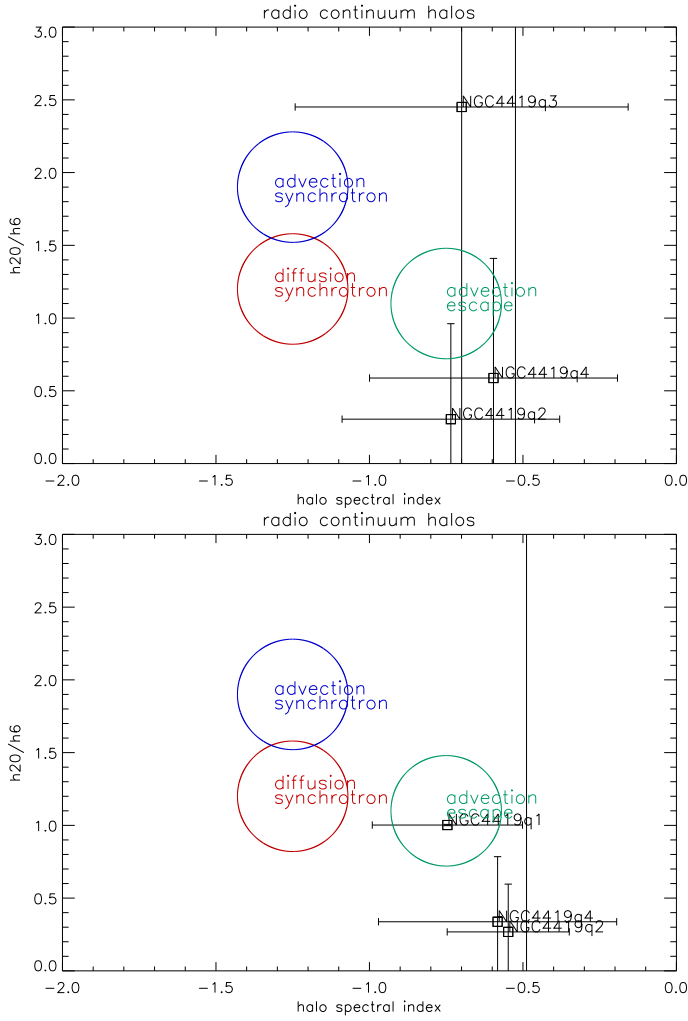


Fig. 10. NGC 4419. Height ratio as a function of the spectral index between 20cm and 6cm; upper panel: mean of all ten models; lower panel: mean of the four best-fit models.

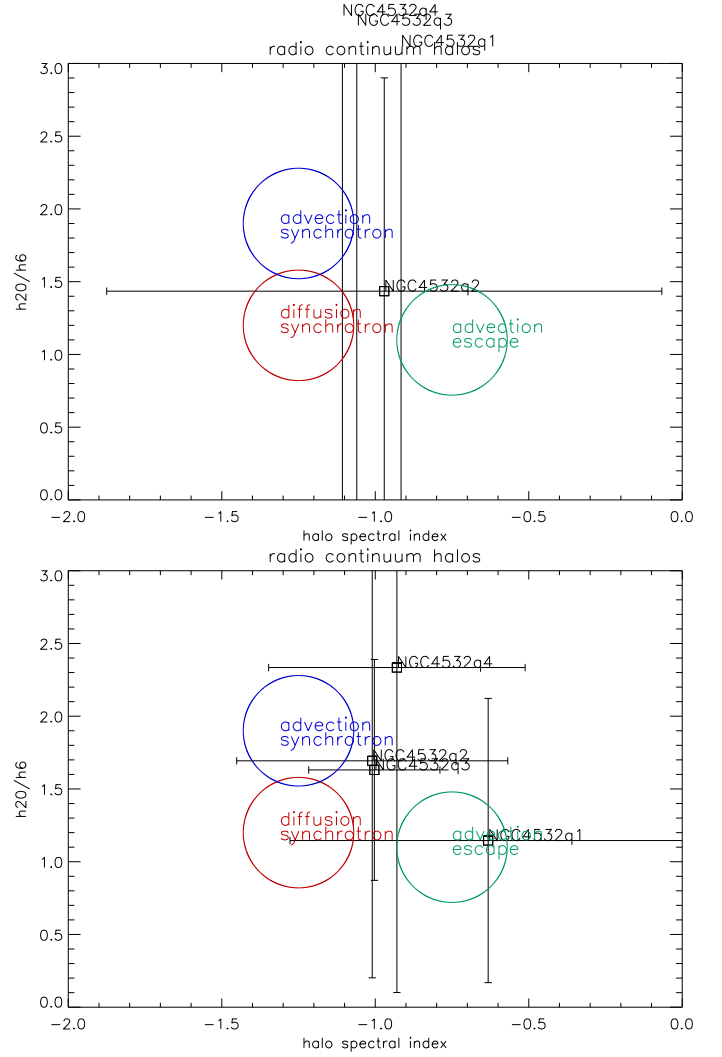


Fig. 11. NGC 4532. Height ratio as a function of the spectral index between 20cm and 6cm; upper panel: mean of all ten models; lower panel: mean of the four best-fit models.

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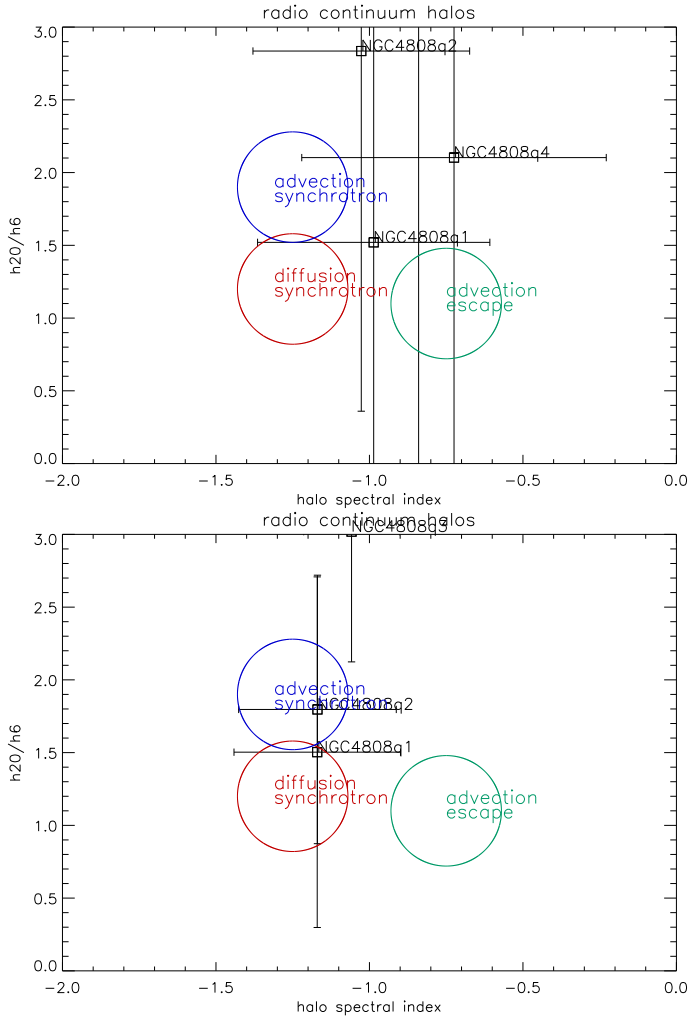


Fig. 12. NGC 4808. Height ratio as a function of the spectral index between 20cm and 6cm; upper panel: mean of all ten models; lower panel: mean of the four best-fit models.

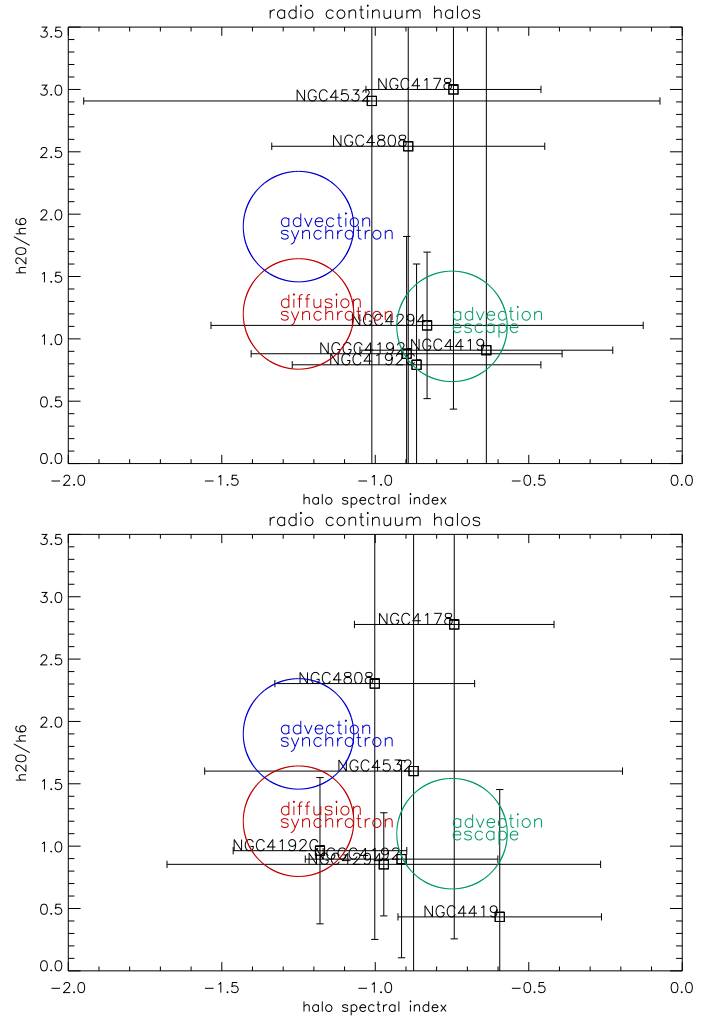


Fig. 13. Quantities averaged over all four quadrants: height ratio at 20cm and 6cm as a function of the spectral index between 20cm and 6cm. Upper panel: based on all ten models; lower panel: based on the four best-fit models.

Appendix A: Observations

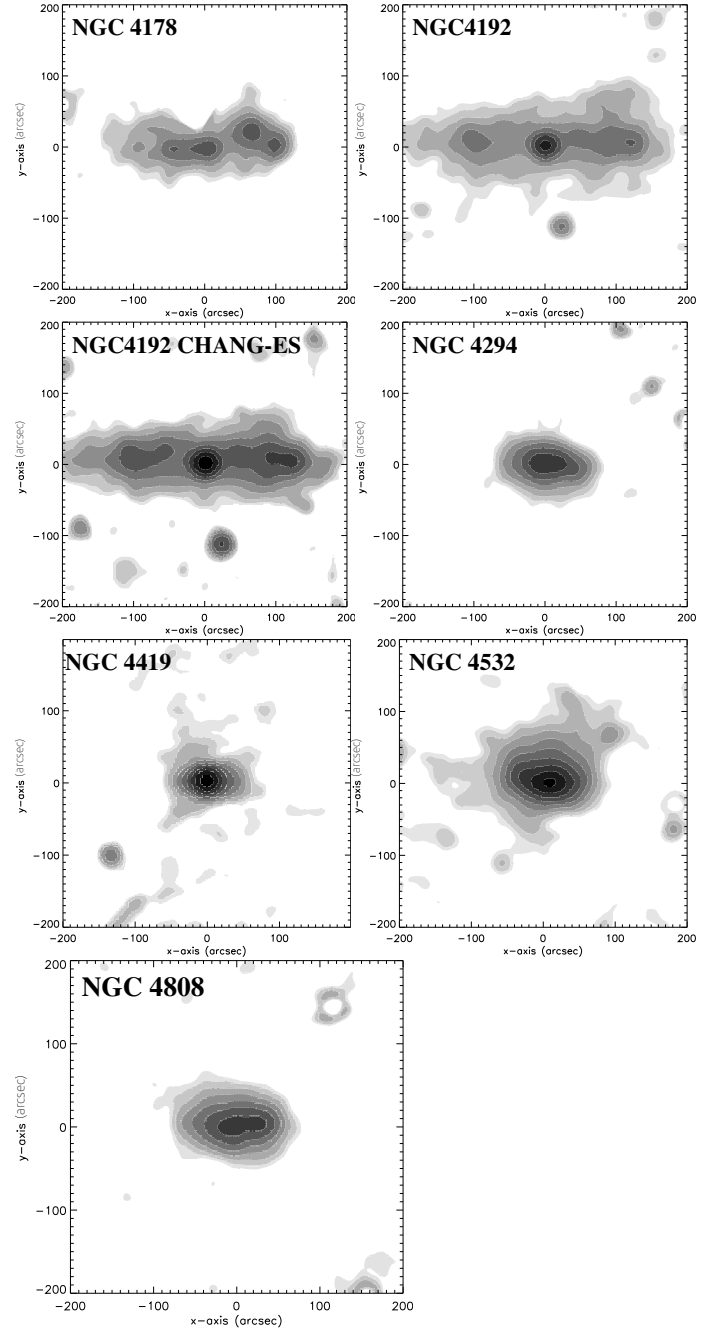


Fig. A.1. Nonthermal radio continuum emission distributions at 6 cm. The contours are $(3, 5, 9, 17, 33, 65, 129, 257, 513, 1025) \times \xi$ with $\xi = (11, 19, 8, 11, 11, 12, 20) \mu\text{Jy/beam}$ for NGC 4178, NGC 4192, NGC 4192CHANGES, NGC 4294, NGC 4419, NGC 4532, and NGC 4808, respectively.

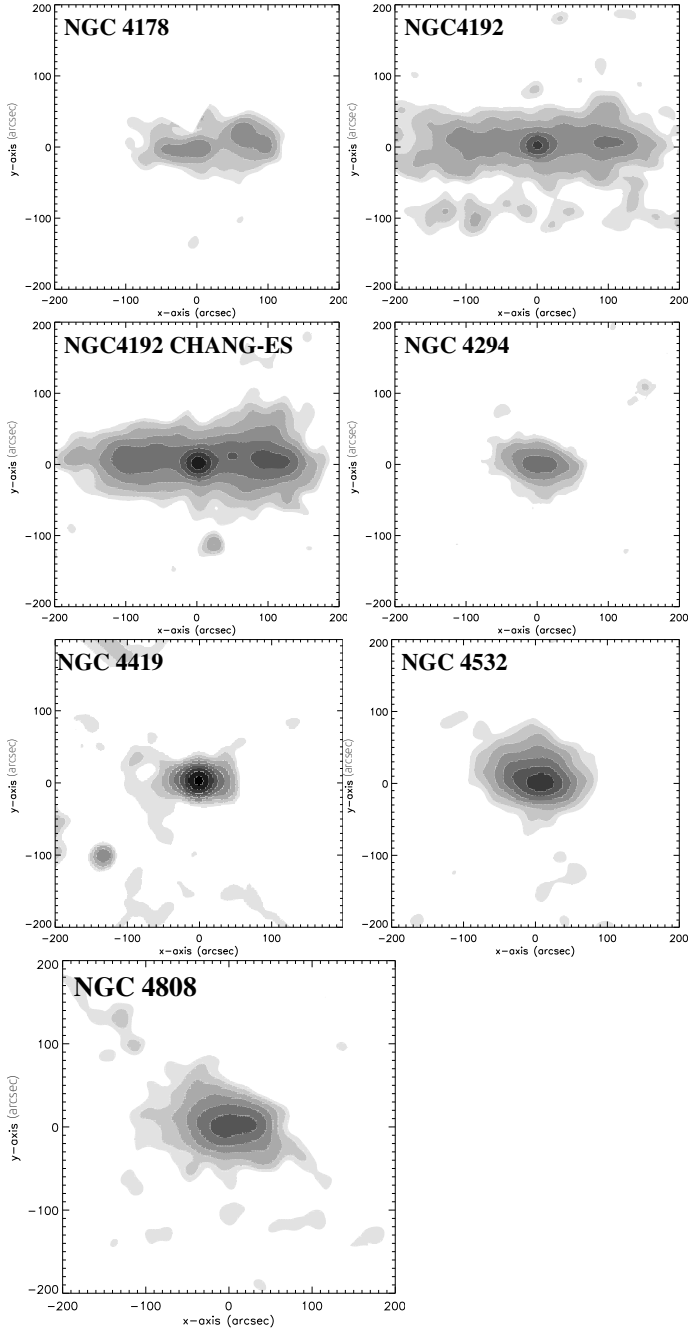


Fig. A.2. Nonthermal radio continuum emission distributions at 20 cm. The contours are $(3, 5, 9, 17, 33, 65, 129, 257, 513, 1025) \times \xi$ with $\xi = (69, 109, 9, 100, 66, 127, 90) \mu\text{Jy/beam}$ for NGC 4178, NGC 4192, NGC 4192CHANGES, NGC 4294, NGC 4419, NGC 4532, and NGC 4808, respectively.

Appendix B: Deprojected star formation maps

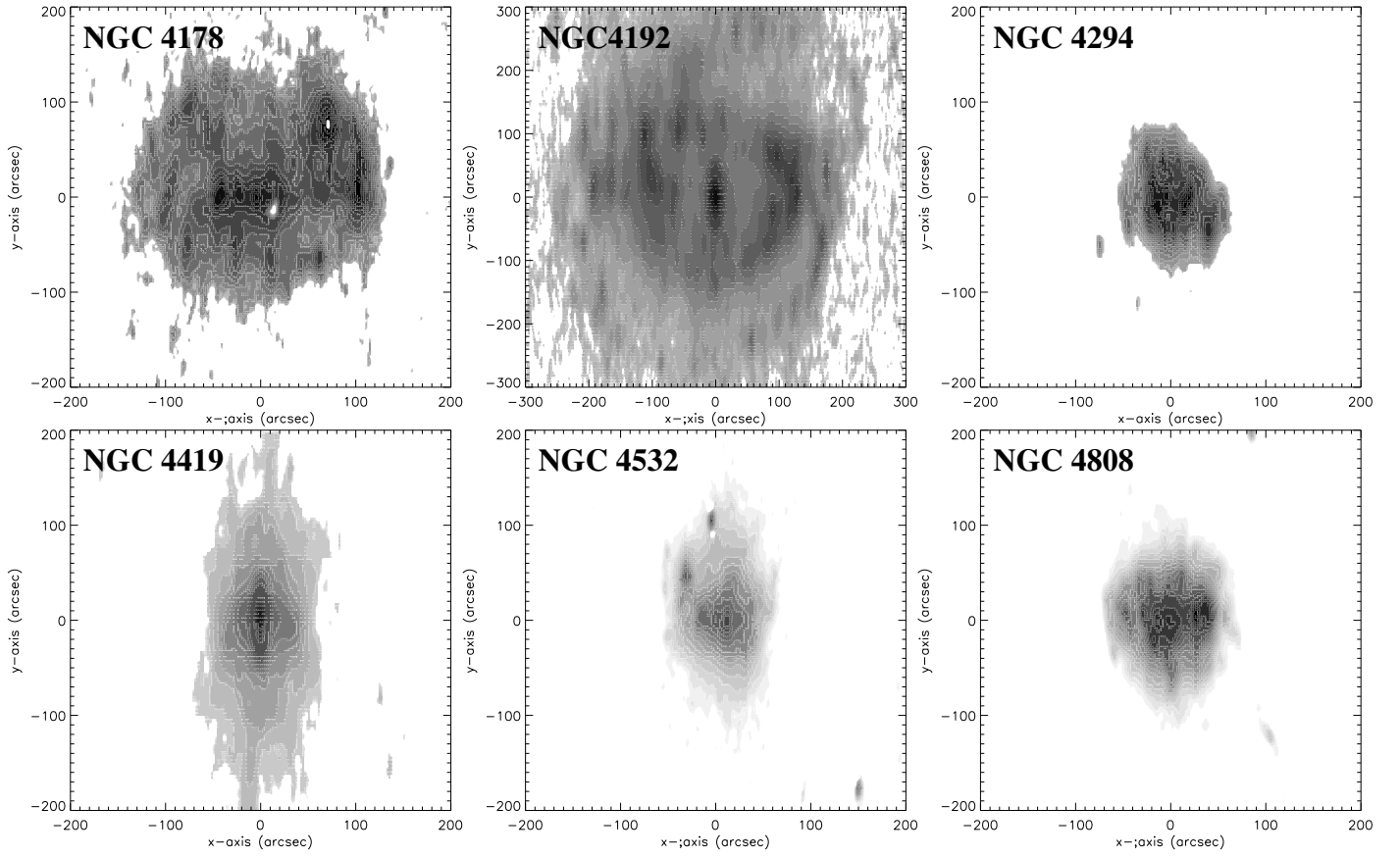


Fig. B.1. Deprojected distributions of the SFR surface density plotted with a square-root transmission function. The units are arbitrary.

Appendix C: Radio continuum halo model

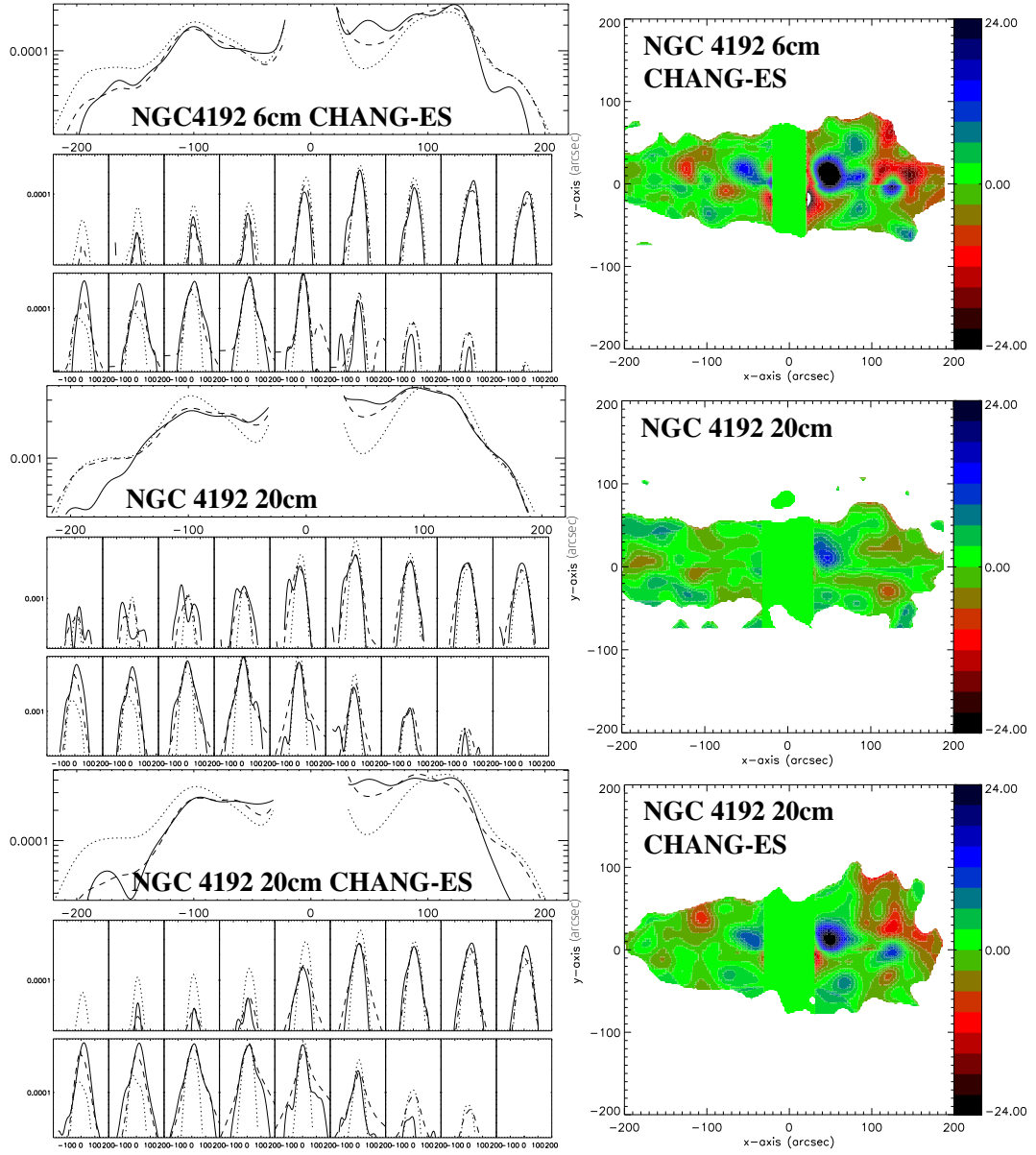


Fig. C.1. Radio continuum halo model of NGC 4192. Left column: profiles along the minor and major axes. Solid lines: observations, dashed lines: model including a thin disk and a halo, dotted lines: model including only a thin disk. All distance are in arcseconds. Right column: maps of the model residuals in units of the rms.

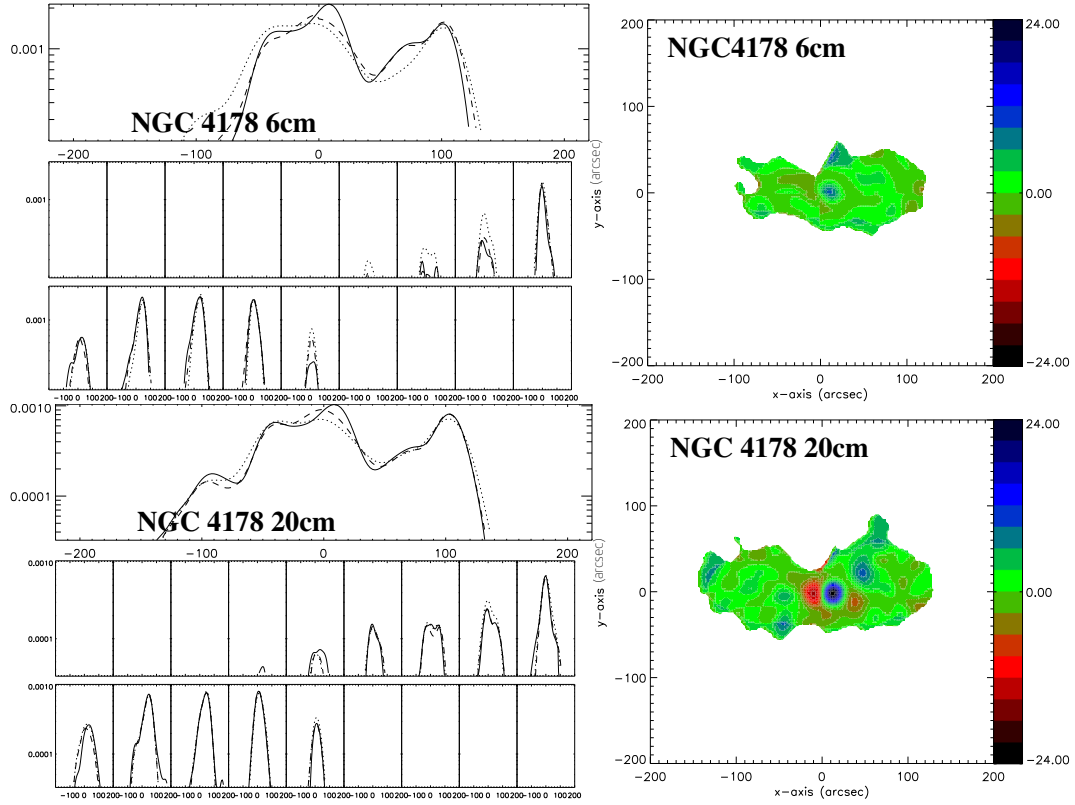


Fig. C.2. Radio continuum halo model of NGC 4178. Left column: profiles along the minor and major axes. Solid lines: observations, dashed lines: model including a thin disk and a halo, dotted lines: model including only a thin disk. All distance are in arcseconds. Right column: maps of the model residuals in units of the rms.

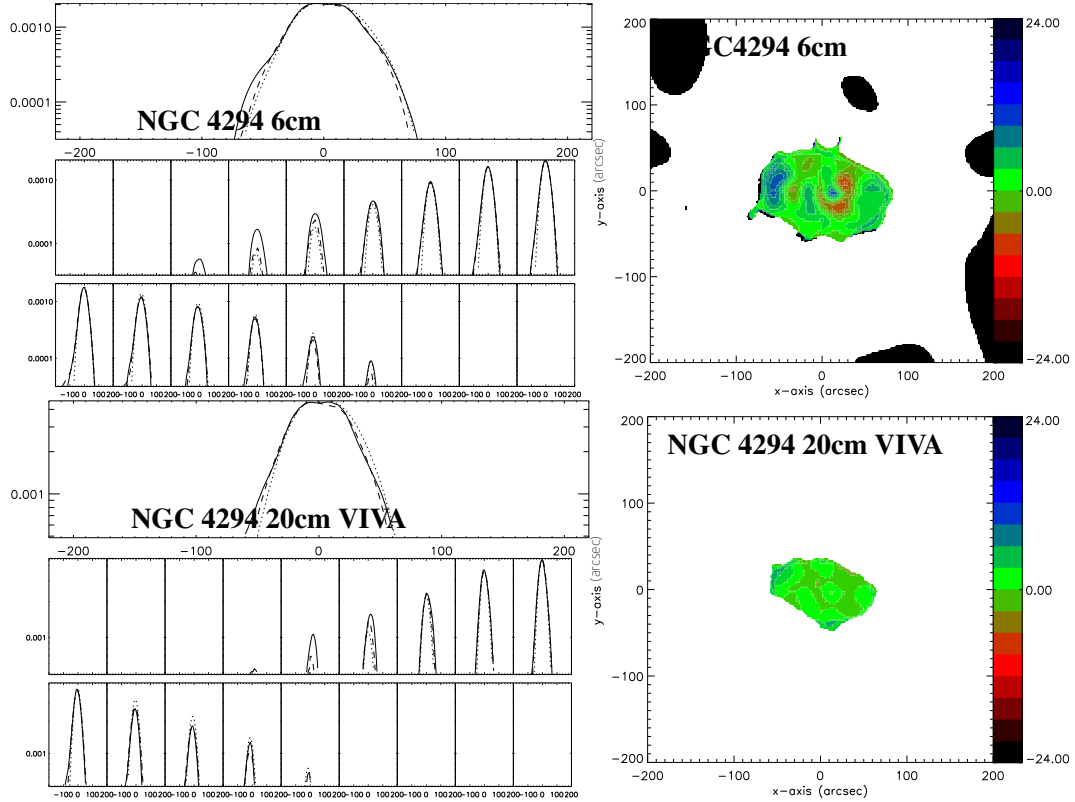


Fig. C.3. Radio continuum halo models of NGC 4294. Left column: profiles along the minor and major axes. Solid lines: observations, dashed lines: model including a thin disk and a halo, dotted lines: model including only a thin disk. All distance are in arcseconds. Right column: maps of the model residuals in units of the rms.

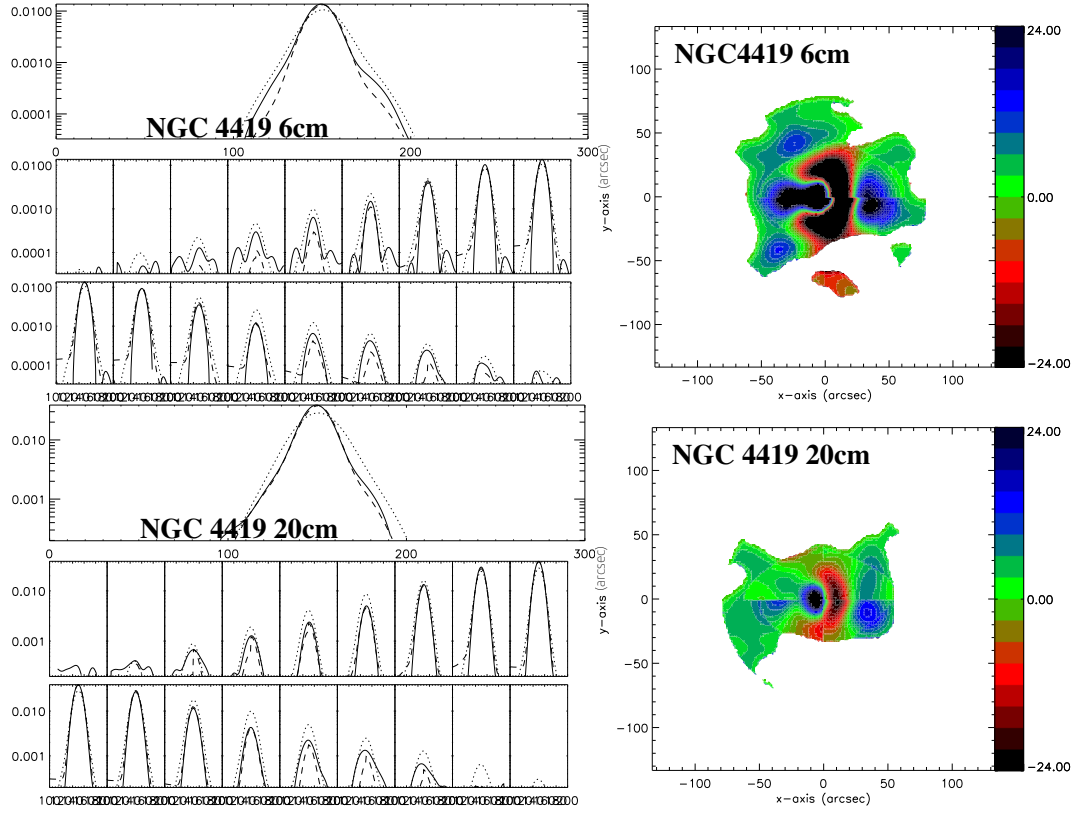


Fig. C.4. Radio continuum halo models of NGC 4419. Left column: profiles along the minor and major axes. Solid lines: observations, dashed lines: model including a thin disk and a halo, dotted lines: model including only a thin disk. All distances are in arcseconds. Right column: maps of the model residuals in units of the rms.

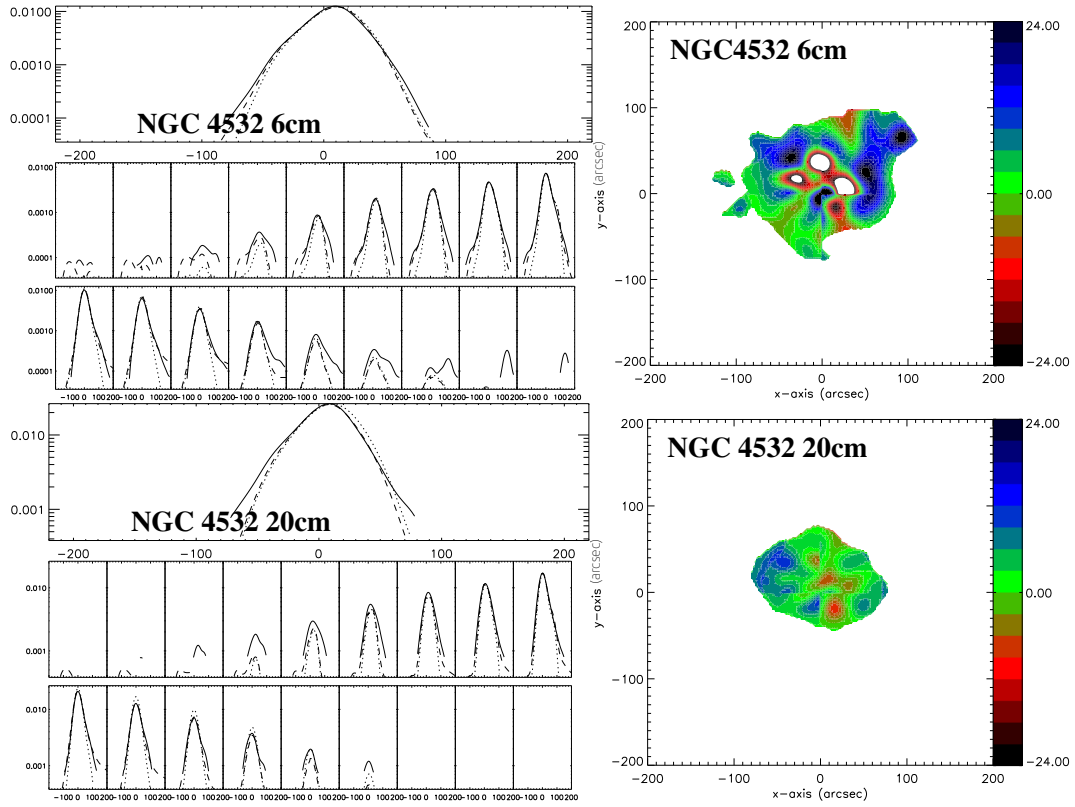


Fig. C.5. Radio continuum halo models of NGC 4532. Left column: profiles along the minor and major axes. Solid lines: observations, dashed lines: model including a a thin disk and a halo, dotted lines: model including only a thin disk. All distance are in arcseconds. Right column: maps of the model residuals in units of the rms.

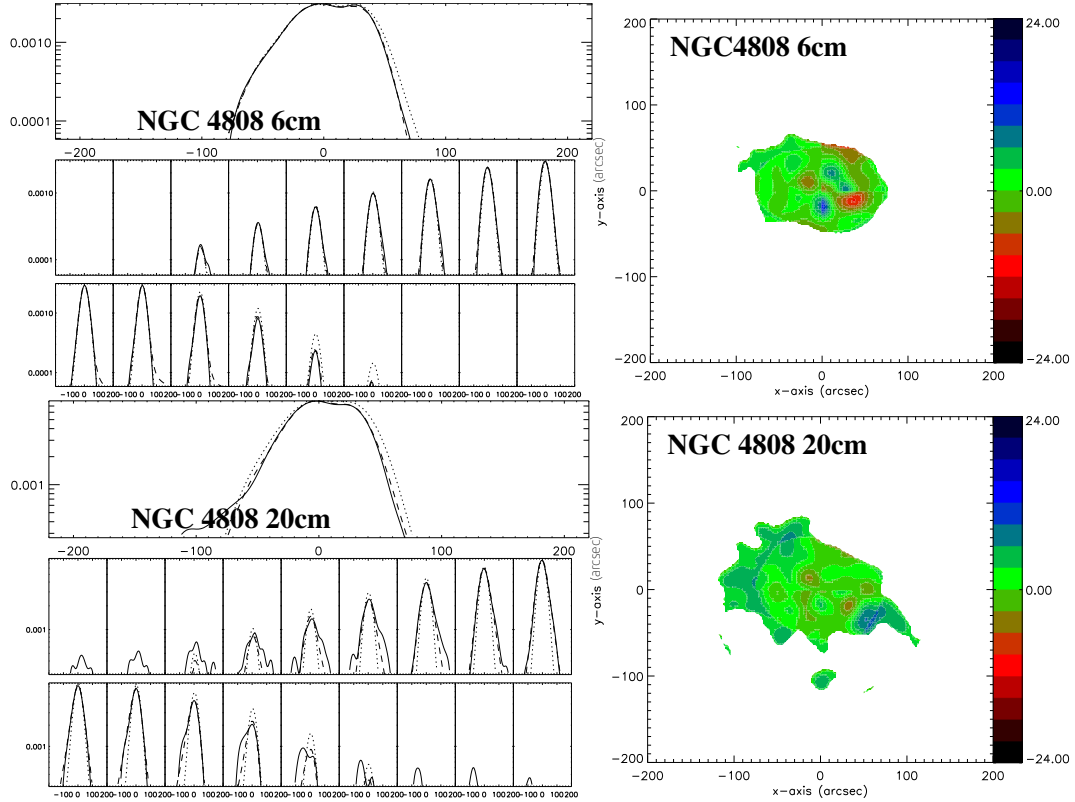


Fig. C.6. Radio continuum halo models of NGC 4808. Left column: profiles along the minor and major axes. Solid lines: observations, dashed lines: model including a a thin disk and a halo, dotted lines: model including only a thin disk. All distance are in arcseconds. Right column: maps of the model residuals in units of the rms.

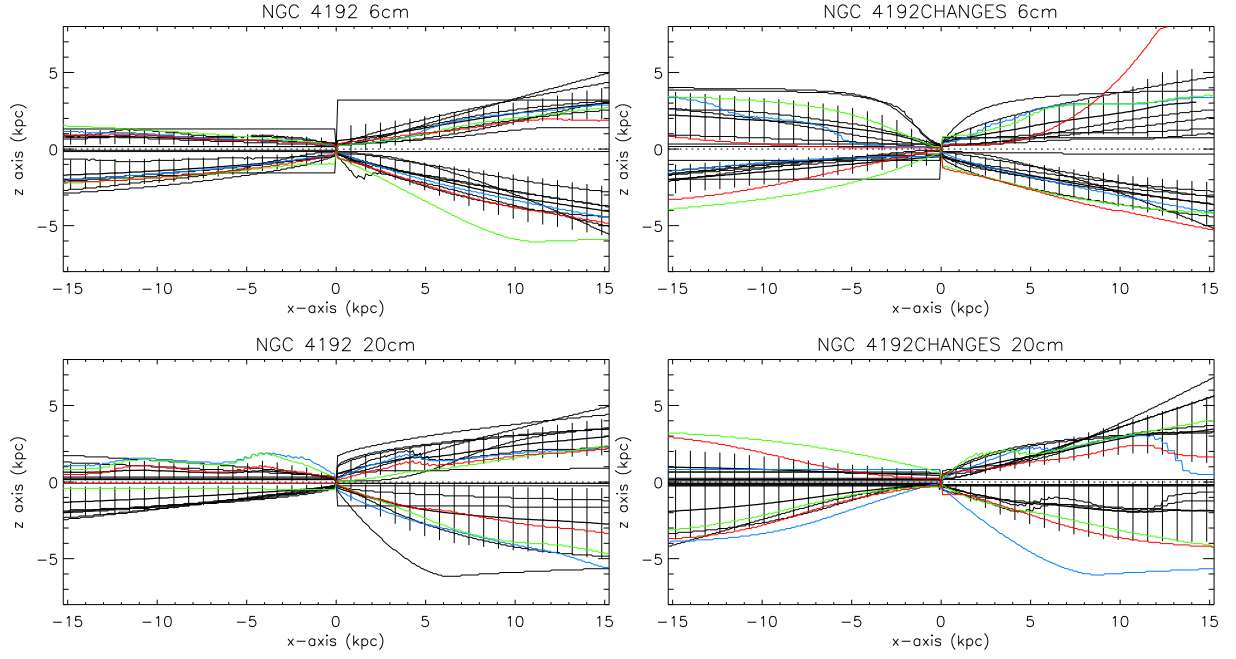


Fig. D.1. Radial profiles of the halo scale height of NGC 4192. All ten models. Lower four panels: best four models. Models with a low χ^2 are red, those with a high χ^2 are blue.

Appendix D: Radio halo scale heights

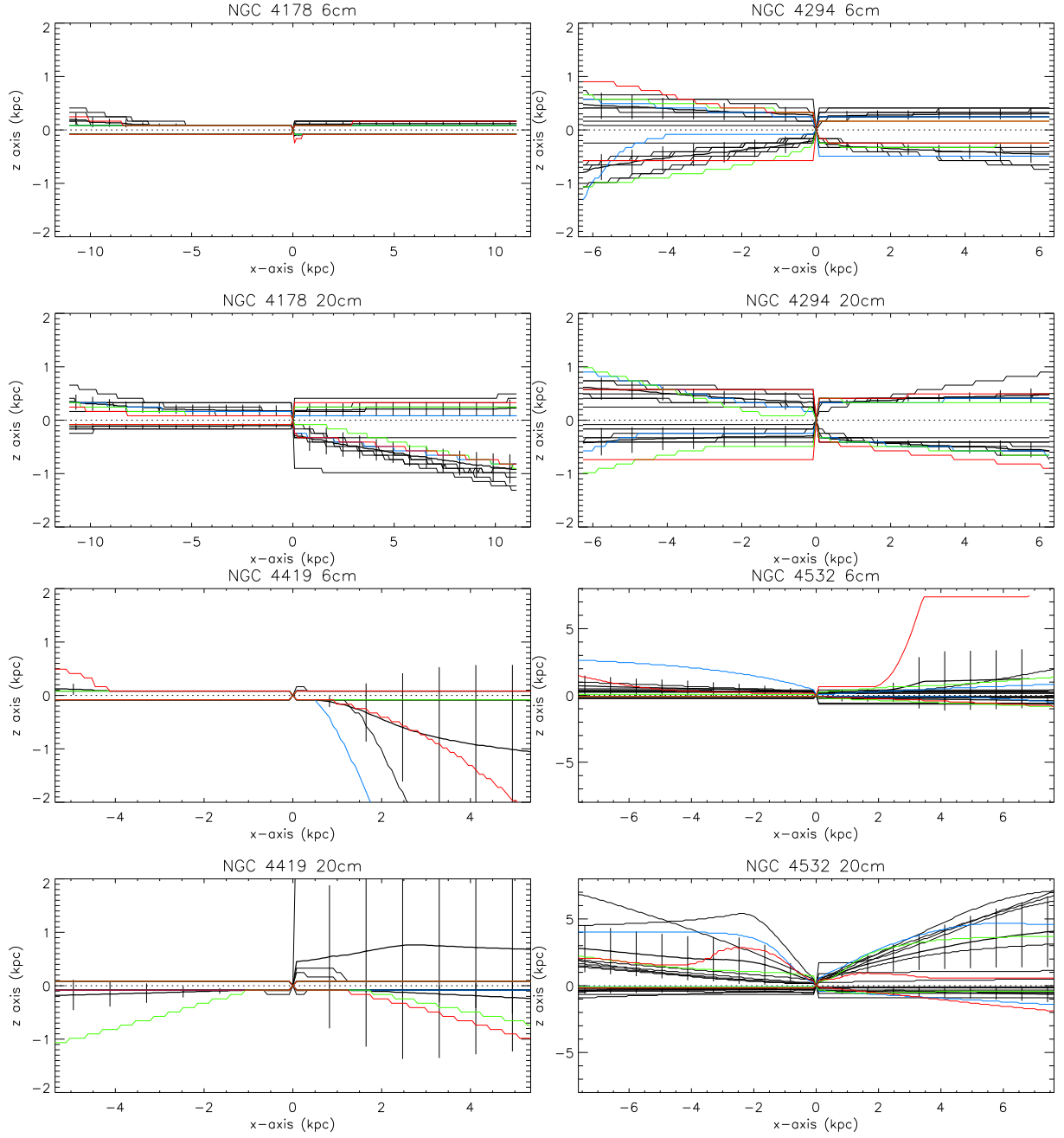


Fig. D.2. Radial profiles of the halo scale height of NGC 4178, NGC 4294, NGC 4419, and NGC 4532. All ten models. Models with a low χ^2 are red, those with a high χ^2 are blue.

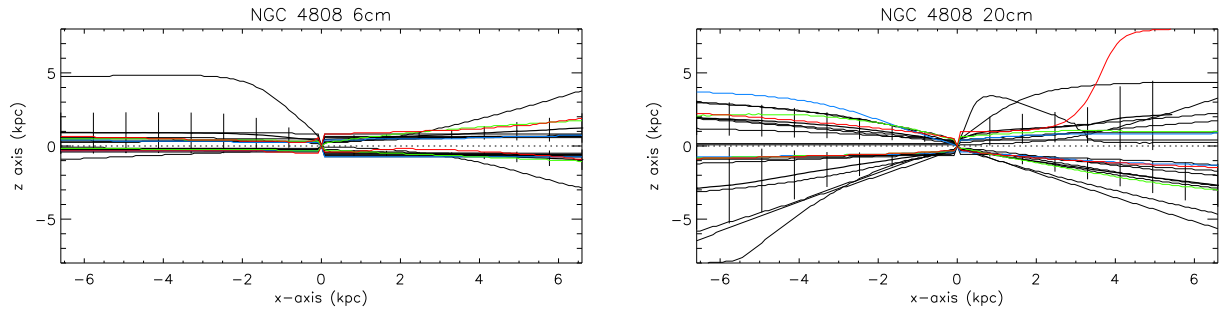


Fig. D.3. Radial profiles of the halo scale height of NGC 4808. All ten models. Models with a low χ^2 are red, those with a high χ^2 are blue.

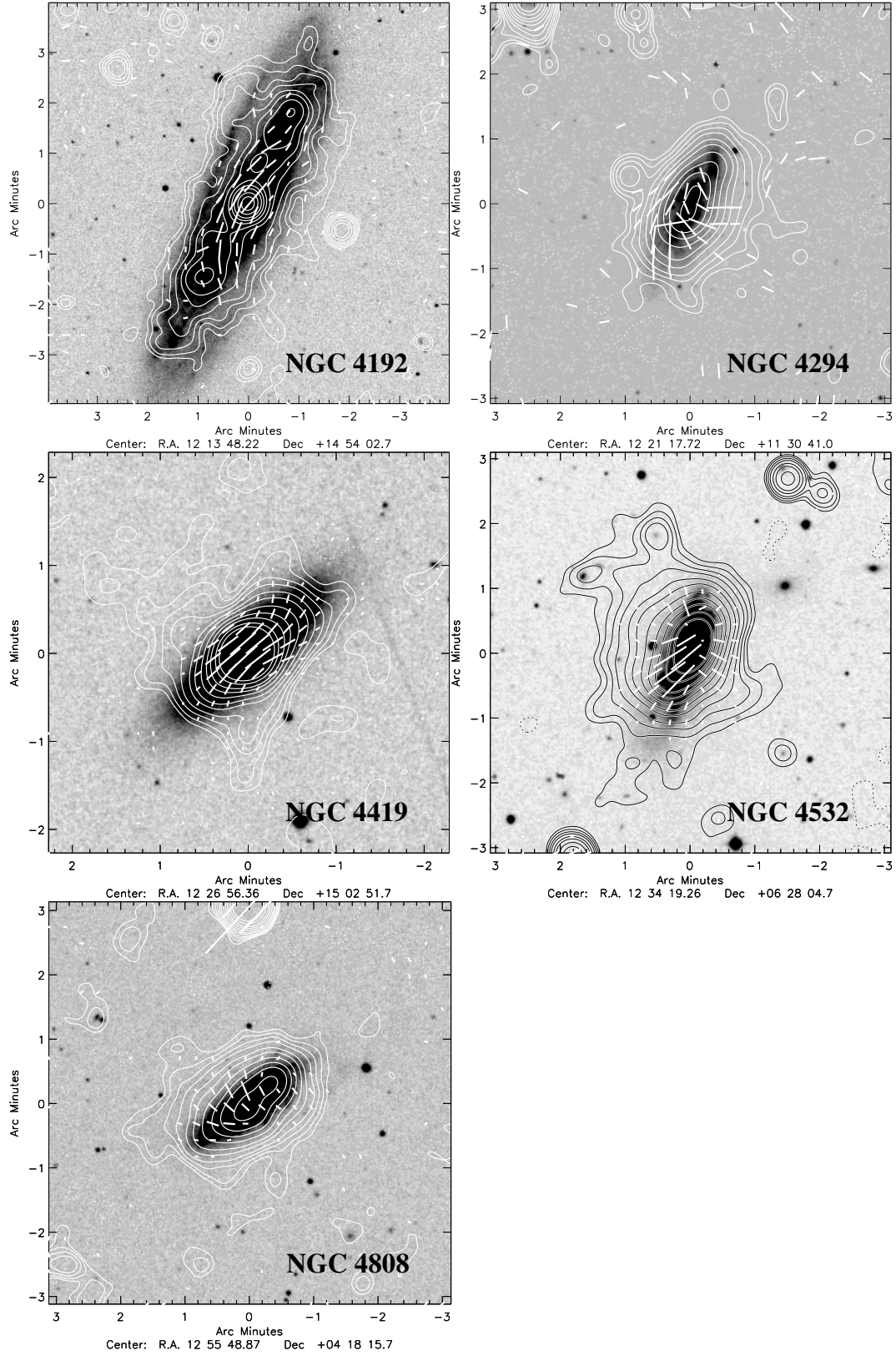


Fig. D.4. Total power emission distribution at 6 cm on DSS B band image together with the apparent B vectors (from Vollmer et al. 2013). Contour levels are $\xi \times (-3, 3, 5, 8, 12, 20, 30, 50, 80, 120, 200, 300)$, with $\xi = 16 \mu\text{Jy}$ for NGC 4192, $\xi = 10 \mu\text{Jy}$ for NGC 4294, $\xi = 11 \mu\text{Jy}$ for NGC 4419, $\xi = 18 \mu\text{Jy}$ for NGC 4532, and $\xi = 14 \mu\text{Jy}$ for NGC 4808.