EVIDENCE FOR A DYNAMICAL HALO AROUND THE EDGE-ON GALAXY NGC 4631

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ABSTRACT

Radio continuum observations at five frequencies between 327 MHz and 10.7 GHz of the edge-on galaxy NGC 4631 confirm the prediction concerning the frequency dependence of the halo extent and the spatial variation of the radio spectral indices in the dynamical halo model made by Lerche and Schlickeiser. The measurements are presented, and a detailed comparison with theoretical predictions is made.

1. Introduction. Four years ago we studied the dynamics of cosmic ray particles in galaxies in the presence of a large-scale galactic wind (Lerche and Schlickeiser 1981a,b; 1982a,b,c — hereinafter referred to as LS1, LS2, LS3, LS4, LS5, respectively). Such a wind gives rise to convection and adiabatic deceleration of particles during their transport, adding to the well established diffusion in partially random magnetic fields and energy loss interactions with ambient matter, magnetic and radiation fields. We pointed out that due to these additional transport terms in particular the spectral behaviour of radio haloes in galaxies caused by synchrotron radiation of relativistic electrons would change at lower frequencies $\nu \ll \nu_D$ with

$$\nu_D = 1 \text{ GHz} \left[\frac{\text{div } \underset{\sim}{u}}{10^{-15} \text{ s}^{-1}}\right]^{-2} (H_\perp / 4\,\mu\text{G})^{-3} \tag{1}$$

where $\underset{\sim}{u}$ is the galactic wind speed. Here we compare our predictions with recent observations of the edge-on galaxy NGC 4631 by Werner (1984, 1985) and Sukumar and Velusamy (1985).

2. Predicted and Measured Radio Emission in the Dynamical Halo Model. In LS4 we solved the steady-state transport equation describing the propagation of relativistic electrons, injected with a power law energy distribution $\propto E^{-p}$ in the galactic disk ($z = 0$), perpendicular to the galactic plane with ("dynamical halo") and without ("static halo") a galactic wind starting with zero velocity in the plane and streaming away from the disk. For both alternatives we predicted remarkable and measurable differences in the behaviour of the total integrated radio flux density $I(\nu)$, the size $E(\nu)$ of the halo perpendicular to the galactic plane at different frequencies, and the spatial variation of the synchrotron spectral index $\delta(z)$ in different ranges of frequency ($S(\nu) \propto \nu^{-\delta}$).

These differences occur at frequencies smaller than ν_D, which corresponds to that electron energy where the energy loss against adiabatic deceleration ($dE/dt = - 1/3 \text{ div } \underset{\sim}{u} \cdot E$) equals that for radiation losses

$(dE/dt = -b_r\,(H^2/8\pi)\,E^2)$. At frequencies larger than ν_D both models predict the same. Consider each quantity in turn:

(a) Inclusion of a galactic wind in the transport equation implies a break of $I(\nu)$ around ν_D from a $\nu^{-(p-1)/2}$-behaviour at low frequencies ($\nu \ll \nu_D$) to a $\nu^{-p/2}$-behaviour at high frequencies ($\nu \gg \nu_D$), i.e. a change in spectral index by $\Delta\Gamma = 0.5$. We noted before (LS3) that NGC 4631 indeed shows this property. In the case of the static model no break is found and the $\nu^{-p/2}$-behaviour holds for all frequencies.

(b) In the static model the size of the halo increases with decreasing frequency, i.e. $E_s(\nu) \propto \nu^{-(1-a)/4}$ where parameter a describes the power law dependence of the particle's diffusion coefficient ($D(E) = D_o\, E^a$). In the dynamical model we find that at frequencies smaller than ν_D, $E_d(\nu) \propto \nu^{a/4}$, whereas at high frequencies $\nu > \nu_D$, $E_d(\nu) = E_s(\nu)$. Figure 1 shows the measured frequency dependence of the halo extent at four different intensity levels for NGC 4631 by Werner (1985). In agreement with our predictions of the dynamical model the extent of the halo does not increase at frequencies less than 1.4 GHz. On the 5% intensity level Werner (1985) finds a dependence $E(\nu) \propto \nu^{0.15\pm0.10}$ at frequencies below 4750 MHz, and a variation of $E(\nu) \propto \nu^{-0.8\pm0.5}$ between 4750 and 10700 MHz. The inferred value for $a = 0.6 \pm 0.4$ is in good agreement with the value $a = 0.6 \pm 0.2$ (Schlickeiser 1983) from studies of the cosmic ray nucleon propagation in our Galaxy.

(c) Figure 2 shows the behaviour of the spectral index gradients in the two models as predicted four years ago (LS2). At high frequencies $\nu > \nu_D$, $\delta(z)$ agrees in both models, whereas there are striking differences at lower frequencies, $\nu < \nu_D$. In the galactic plane ($z = 0$), $\delta_d(z=0)$ is by 0.25 smaller than $\delta_s(z=0)$. This difference may be doubled (0.50) if instead of the infinitely thin line source of electrons at $z = 0$ an extended source distribution is taken (LS5, Lerche and Schlickeiser 1985). With increasing height $\delta_d(z)$ first slightly decreases before a sharp increase occurs. On the other hand, $\delta_s(z)$ increases gradually with increasing height.

These predictions can be compared with the variation of the radio spectral indices as a function of height above the plane measured in NGC 4631 by Sukumar and Velusamy (1985), and shown in Figure 3. The excellent agreement with the predictions of the dynamical model in Figure 2 is apparent. The high-frequency (610 - 1412 MHz) index shows a gradual steepening with z, as expected for the electron spectrum evolution due to synchrotron losses. The low-frequency (327 - 610 MHz) index flattens with increasing z (up to about 3 kpc) and then steepens with height, as predicted. The difference $\Delta\delta$ between the high- and low-frequency spectral indices near the plane (at $z = 0$) is ~ 0.35, well within the theoretical range from 0.25 - 0.5. Similar results have been obtained by Werner (1984) who compared spectral indices derived from measurements at 608.5, 1412, 4750 and 10700 MHz. He also proved that the radio halo emission is synchrotron radiation by measuring the linear polarization.

3. Conclusions. The radio measurements of Werner (1984, 1985) and Sukumar and Velusamy (1985) of the external edge-on galaxy NGC 4631 con-

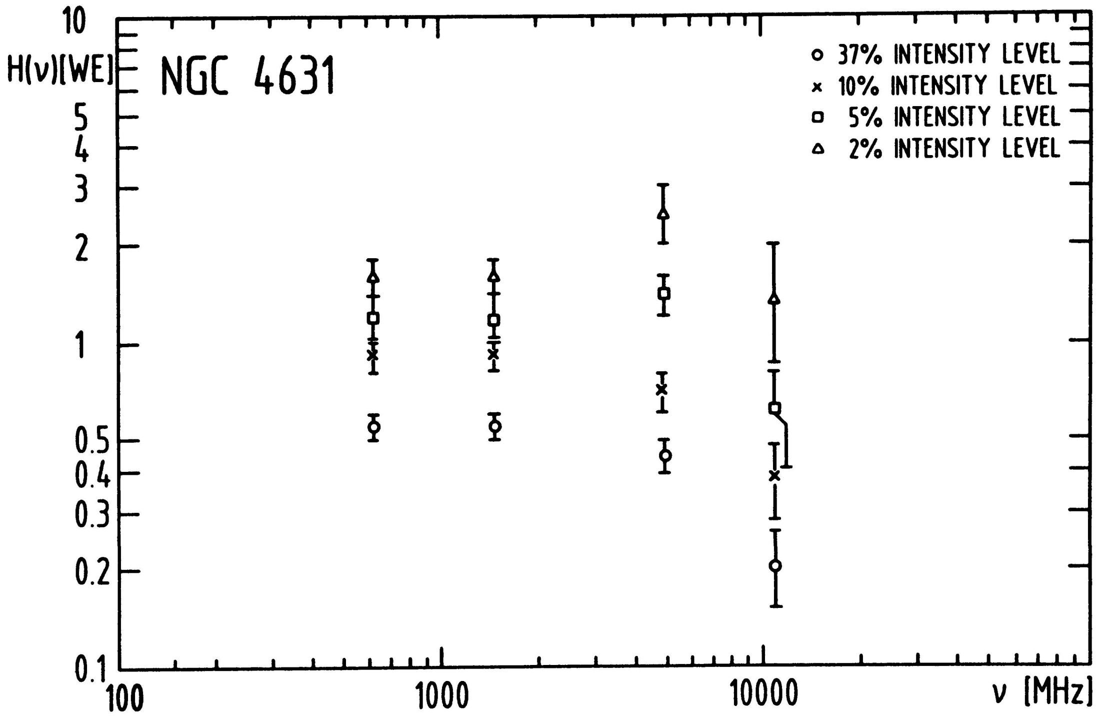

Fig. 1: Frequency dependence of the halo size of NGC 4631 at different intensity levels (from Werner 1985)

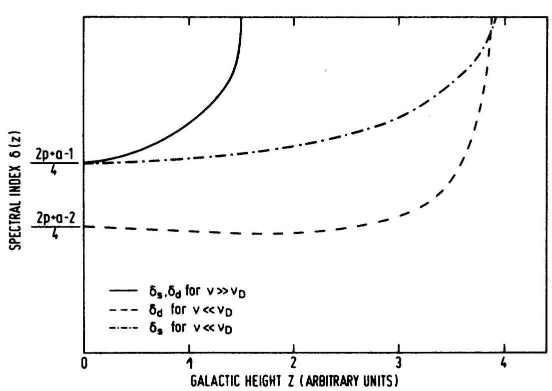

Fig. 2: Predicted variation of the synchrotron spectral index for small ($\nu \ll \nu_D$) and large ($\nu \gg \nu_D$) frequencies in the static (s) and dynamical (d) model. p is the spectral index of injected electrons ($\propto E^{-p}$) in the plane $z = 0$; a the assumed power law dependence of the diffusion coefficient ($D \propto E^a$) on the energy of relativistic electrons (from Lerche and Schlickeiser 1981b).

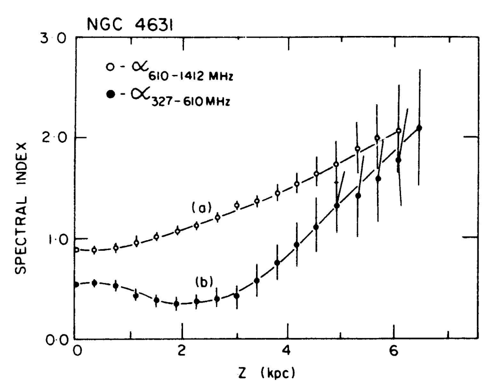

Fig. 3: Measured variation of the radio spectral index as a function of height above the plane in NGC 4631: (a) α(610 - 1412 MHz), (b) α(327 - 610 MHz) (from Sukumar and Velusamy 1985)

firmed the predictions of LS (1981, 1982) on the spectral behaviour of its radio halo in the presence of a large-scale galactic wind. This is unambiguous evidence for the existence of large-scale convective motion of matter from the disk into the halo region in NGC 4631. Since NGC 4631 is morphologically similar to our Galaxy, conclusions drawn for NGC 4631 also apply to our Galaxy.

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