HALO OF NGC 4631 AND MODELS OF COSMIC-RAY TRANSPORT

R. Cowsik and S. Sukumar
Tata Institute of Fundamental Research, Bombay 400005
India.

ABSTRACT

The halo of edge-on spiral galaxy of NGC 4631 is studied from 327 MHz to 10700 MHz to delineate the models of cosmic-ray transport. Preliminary studies show that the spectral steepening as a function of height above the plane can be understood in terms of the simplest cosmic-ray transport models, viz. simple isotropic diffusion in an infinite medium. More detailed study will be presented at the time of the conference.

1. Motivation. Twenty-seven years ago, Ginzburg in his classic paper emphasized the importance of the study of galactic halos in understanding the modes of cosmic ray transport and acceleration [1]. Despite his continued insistence [see for example ref.2] the observational status is progressing rather slowly. As emphasized by Ginzburg spiral galaxies seen edge-on are ideal for the study of the distribution of matter, cosmic rays and magnetic fields in the halo. Only recently, radio maps of spiral galaxies with adequate resolution and sensitivity at different frequencies have become available [3-6]. We would like to focus our attention on NGC 4631 which is a nearly edge-on Sc-spiral subtending more than 15 arc min along the major axis. Special efforts were made to map this source at 327 MHz by using the Ooty Synthesis Radio Telescope [7-8]. The importance of having a good map at such low frequencies are two fold : first, since the lower energy electrons are expected to suffer smaller synchrotron and Compton losses they can be transported to great distances efficiently so that the outer extent of the halo can be better delineated; second, the low frequency observations when combined with the earlier observations at 610 MHz and 1412 MHz can be used to study the variations in the spectral index of the halo as a function of scale height above the galactic plane. The map obtained with OSRT [8] is reproduced in figure 1. Since the distance of the galaxy is 5.2 Mpc [9] each arc minute corresponds to a length of 1.5 kpc. Notice that the halo extends up to 7.5 kpc radius and the aspect ratio at $\sim$ 50 mJy is $\lesssim$ 2.

In contrast with the rather limited observational data on halos, the theoretical studies on cosmic-ray propagation have become very complex and sophisticated. Recently Lerche

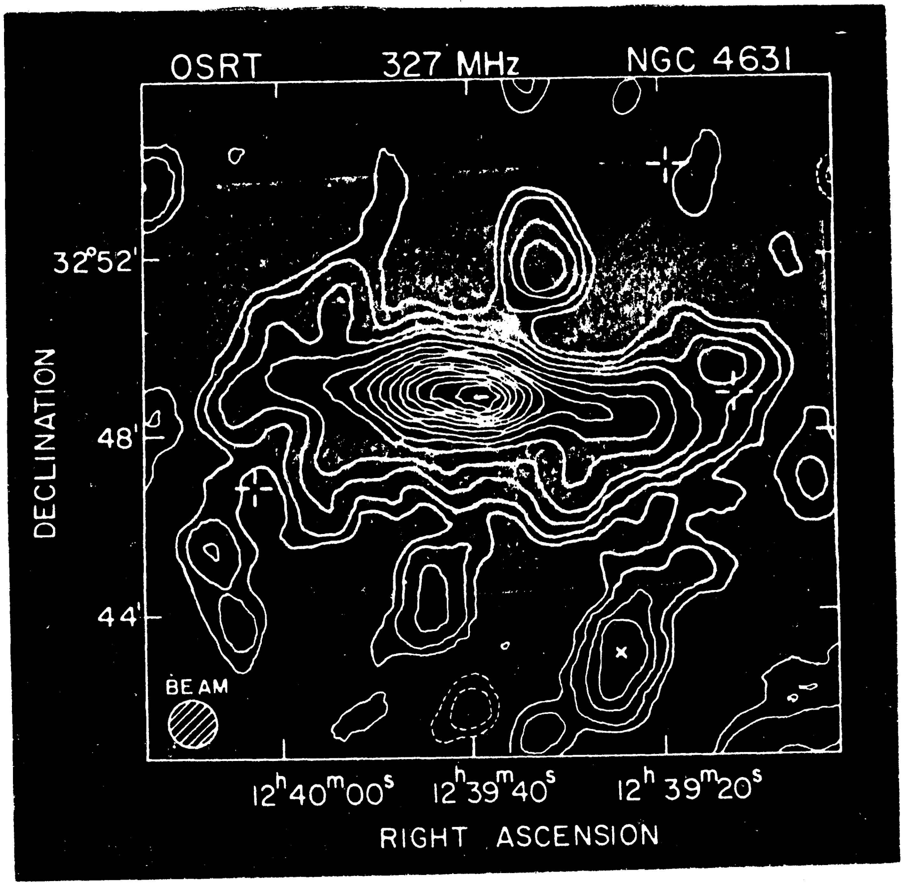

Fig.1 Overlay of ORST map of NGC 4631 at 327 MHz with a resolution of 60 x 60 arcsec^2, on a Palomar Sky Survey print. The first four contours are at 7.5, 15, 30, 45 and then increasing with contour interval of 30 mlv per beam. Negative contours are dashed. Courtesy-'60 National Geographic Soc.-Palomar Sky Survey.

and Schlickeiser [10] have published solutions to the propagation equations including a variety of processes like energy-dependent diffusion, convection, adiabatic deceleration, radiative losses and so forth. In principle one would be able to compare the predictions of such theories with observations to assess the importance of the various physical processes that are operative in the source. The number of parameters that are needed to specify the theoretical models are quite large, especially when we include those needed to specify the distribution of the sources of cosmic-ray electrons and protons which in interactions with the gas will generate secondary positrons and electrons. Because of this a very many different set of parameters can give an adequate fit to the data and we would not have gained much understanding. Keeping in mind these points we start with the simplest possible transport theories and see to what extent the observations can be explained. If there be any unexplained feature we would progressively make the models more sophisticated. At the time of writing this only a very preliminary study has been completed; we present the results of this study here and further developments would be presented at the time of the conference.

2. The Simplest Model for Galactic Halos. Consider a distribution of sources of cosmic-ray protons and electrons (assumed to be identical) embedded in an infinite diffusion medium which is homogeneous and isotropic. The radiative losses suffered by the electrons during transport is taken to be independent of position. The transport of protons is independent of energy. Thus the most general transport kernel μ ($\underline{r}$, $\underline{r}'$, E, E', t1, t2) simplifies for protons to

$$\mu(r,t) = [2\pi^{1/2}(Kt)^{3/2}]^{-1} \exp(-r^2 / 4Kt) \tag{1}$$

Here $r = |\underline{r} - \underline{r}'|$, $t = [t-t']$, K is the diffusion constant and μ is defined for an unit source strenght per unit volume per unit energy interval and per steradian. Under conditions of steady state the kernel integrates to

$$\mu(r) = [Kr]^{-1} \tag{2}$$

The spatial part of the source distribution is taken to be the same for both the proton and the electron components.

$$N(r') \sim \exp - (\omega'/\omega_o + |z'|/z_o) \tag{3}$$

where axial symmetry is assumed and ω, z,(and Θ) are the cylindrical co-ordinates. Now the spectral density of cosmic-ray protons is written as

$$S_p \sim \int N_p(r',E) (K|\underline{r} - \underline{r}'|)^{-1} d^3r' \tag{4}$$

The source function for the secondary electrons and positrons is proportional to the product of the gas density G(r) and the spectral density of protons

$$N_{sec}(E,r) = \int \sigma(E',E) S_p(E',r) G(r) dE' \tag{5}$$

where $\sigma(E',E)$ is the cross-section per particle of energy E' colliding with a gas atom to generate an electron or positron per unit energy interval at E through the decay of the secondary mesons and muons etc. The gas density G(r) is taken to be

$$G(r) \sim G_o \exp - (\omega/\omega_g + |z|/z_g) \tag{6}$$

The spectral density of primary and secondary electrons at r are now given by

$$S_e \sim \int_0^\infty N_e(E',r')\ \mu(E,E',\ |r-r'|,\ t)\ dE'\ dt \qquad (7)$$

$$S_{sec} \sim \int N_{sec}\ (E',r')\ \mu(E,E',|r-r'|,t)\ dE'\ dt \qquad (8)$$

with obvious notation. In the simplified model of cosmic ray transport considered here the kernal μ in equations(7), (8) is given simply by

$$\mu(E',E,r,t) = \delta\left(E' - \frac{E}{1-bEt}\right)\left[2\pi^{1/2}(Kt)^{3/2}\right]^{-1} \exp-(r^2/4Kt) \qquad (9)$$

with b representing the rate of energy loss of an electron of unit energy. The function allows easy integration of equations(7) and (8). We compare in Fig.2 the expected variation of the spectral index at 1000 MHz with the observed variation with z. One sees that even this simple model gives a reasonable representation of the observations.

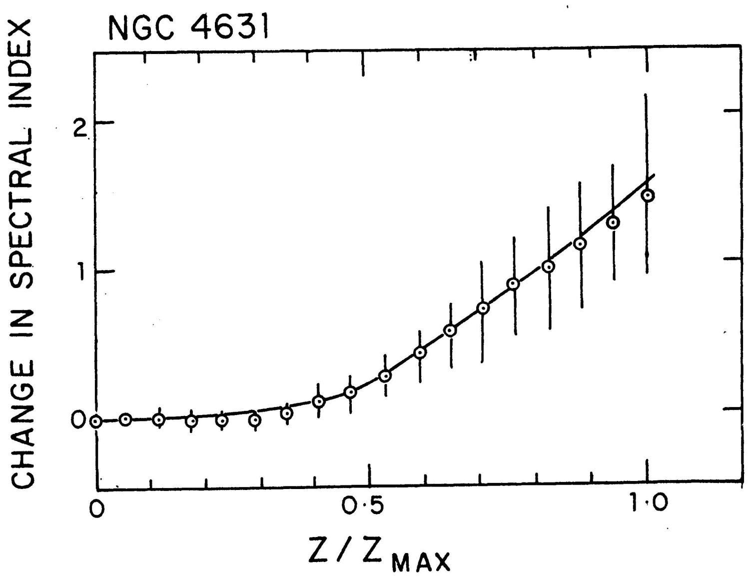

Fig.2. Spectral index variation along Z direction. Observed points circled; solid line indicates model fit.

References.
1. Ginzburg,V.L.(1958),Progress in elementary particle and cosmic ray physics, 4, 438.
2. Ginzburg,V.L.(1985),in Cosmic Pathways(Tata McGraw Hill, ed.R.Cowsik).
3. Ekers,R.D.and Sancisi,R.,(1977), Astron.Astrophys.54, 973
4. Beck,R. et al (1979), ibid, 77, 25.
5. Klein,U. and Emerson, D.T.(1981), ibid, 94, 29.
6. Hummel,E. (1980), ibid Suppl., 41, 151.
7. Swarup,G. (1984), J.Astron.Astrophys. 5, 139.
8. Sukumar,S. and Veluswamy,T.(1985), MNRAS, 212, 367.
9. Sandage, A.and Tammann,G.A.(1975),Astrophys.J.,196, 313.
10. Lerche, I.and Schlickeiser,R.(1982),Astr.Astrophys.107,148.