GAMMA-RAY EVIDENCE FOR A GALACTIC HALO

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Abstract: γ-ray data favor a cosmic-ray propagation halo comparable with the thickness of the primary radio emission disk of our Galaxy and the halo seen around NGC891.

1. DEFINITIONS OF GALACTIC HALOS

We define a galactic halo to be a region containing relativistic particles in significant enough numbers to have observable effects. Such a region must also extend above and below the galactic plane for a distance larger than twice the scale height of the source region. Using these defini- tions, we distinguish between a cosmic-ray electron halo and a cosmic-ray nucleon halo, the former occupying a volume less than or equal to that occupied by the latter because electrons can suffer significant energy loss by synchrotron emission and Compton interactions during their life- time whereas nuclei do not. The electron halo is manifested through ob- servations of radio synchrotron emission and x-ray and γ-ray production from Compton interactions. The nucleon halo, which plays a significant role in the dynamics of the interstellar medium and in determining the propagation characteristics of cosmic rays, is not directly observable by γ-ray astronomy because of the extremely tenuous nature of the gas far from the galactic plane. (Cosmic ray nucleons must interact with gas in order to produce observable γ-rays). However, indirect arguments using data on the distribution of γ-radiation in the plane can be used to place limits on the dimensions of the nucleon halo (Stecker and Jones 1977). γ-ray observations provide the only means for studying the nucleon halo.

Both electron and nucleon halos can be separated into two regions. There is (1) a region where particle propagation is dominated by diffusion and there is a significant probability for particles in the region to return to the plane. Since this region will generally have the form of a thick disk, I will call it the diffusion disk. (2) I also define a region where convection or free escape dominates over diffusion. Particles in this region will not return to the propagation disk (Jones 1978). This region, which I will call the exodisk, (Stecker 1977) will generally have a lower particle density but may still have observable radio emission (Webster 1975). We will consider only dynamical (Ipavich 1975, Jokipii 1976,

Owens and Jokipii 1977) and diffusion halos to be physically plausible;
trapping, closed or "leaky box" models have no physical basis and also
contradict evidence of large scale gradients in the galactic cosmic ray
distribution (Stecker 1977, Stecker and Jones 1977).

2.   EXISTENCE OF A PROPAGATION DISK

The γ-ray data from both SAS-2 (Fichtel et al. 1975) and COS-B (Bennett
et al. 1977) require that cosmic-rays not be strictly confined to spiral
arms; they must diffuse into a larger propagation region. If cosmic rays
were strictly confined to well defined spiral arms with a large arm in-
terarm gas ratio, as in the gas (Roberts 1977), the result would be spiral
arm peaks in the γ-ray longitude distribution which would be too pronounced
and too intense in comparison to the data (Stecker 1977, Stecker and Jones
1977). As a specific example, we may note the lack of a Sagittarius arm
feature at $\ell = 50°$ in the γ-ray data.

Further evidence for a propagation disk comes from analysis of the non-
thermal radio continuum data which shows that confinement of cosmic rays
to spiral arms is untenable (French and Osborne 1976) and that there is
a strong disk component of nonthermal emission (Price 1974). Most measure-
ments of ^{10}Be in the cosmic-rays (e.g. Garcia-Munoz et al. 1977) indicate
that cosmic rays have a mean lifetime in the range $(1-2) \times 10^7$ yr and have
traversed a gas of mean density during that time of 0.15-0.3 cm^{-3}. If
this is indeed the case, the cosmic rays within ~ 1 kpc of us must have
spent most of their time in regions of quite low density since the mean
density in the galactic disk in the solar vicinity is ~ 1 cm^{-3} (Gordon
and Burton 1976, Jenkins 1977). The ^{10}Be situation is still not completely
settled (see summaries of the data given by Stecker and Jones 1977 and
Ormes and Freier 1978). Ormes and Freier (1978) have shown that one can
build a model of cosmic-ray propagation which is consistent with the data
on cosmic-ray composition as well as the radio and γ-ray data assuming a
mean cosmic ray age of $(1-2) \times 10^7$ yr. Dynamical considerations (Badhwar
and Stephens 1975, Parker 1977) also favor a thick propagation disk model.

3.   LATITUDE DISTRIBUTION OF γ-RAYS AND THE ELECTRON HALO

Fichtel et al. (1978) have considered the latitude distribution of γ-rays
observed by SAS-2 to be made up of two components of the form $A+BN_{HI}$.
Component A has a very steep energy spectrum. It is most likely of cosmo-
logical origin (Stecker 1977, 1978a) and is so isotropic as to exclude
large quasispherical halos with radii less than 45 kpc (Fichtel et al.
1978). The isotropy and energy spectrum observations rule out the large
γ-ray halo models discussed by Worrall and Strong (1977) (although thin
halo models considered by Worrall (1977) are consistent with the conclu-
sions of this section). We will thus consider that any extended γ-ray halo
ewith dimensions ~ 10-20 kpc be either non-existent or too weak to be
observable at present, a conclusion which has interesting implications
for high energy cosmology (Stecker 1978b.) We do, however, consider the
possibility that the component designated by Fichtel et al. (1978) as
BN_{HI}, which they have shown to have roughly linear dependence on N_{HI} for
$|b| > 10°$, can also represent the sum of a number of disk components which

scale roughly as csc $|b|$. Such a rough dependence has previously been
shown by Fichtel et al. (1977). This component can also include a con-
tribution from Compton interactions of cosmic ray electrons in the radio
disk (Stecker 1977) as well as bremsstrahlung and π°-decay γ-rays arising
from cosmic ray interactions with both HI and H_2 in the gas disk. The
electron halo will then be identified with a thick disk-shaped propagation
region which extends somewhat further than the radio disk if the magnetic
field falls off with distance from the plane. γ-rays from this "electron
halo" then arise from Compton interactions between electrons and the
various photon fields (starlight, far infrared, universal microwave) in
the galactic neighborhood. In support of this hypothesis we note that
Fichtel et al. (1978) have also found a good correlation between the γ-
ray flux and 150 MHz radio flux for $|b|>10^\circ$. Working from this type of
model Schlickeiser and Thielheim (1977) have obtained an effective half-
thickness of the electron halo h $\sim$ 3 kpc. Stecker and Jones, taking
various uncertainties into account have obtained the results h = 2$\pm$2 kpc.

To reexamine this problem here, we first consider the γ-rays arising in the
matter disk from π°-decay and bremsstrahlung (π+B). Using the reddening
data of Heiles (1976) and the relation between reddening and total hydro-
gen column density N_{HI+H_2} given by Jenkins (1977), the π°-decay produc-
tion rate of Stecker (1970), and the bremsstrahlung production rate cal-
culated using the low energy electron spectrum derived by Goldstein et al.
(1970), we estimate the integral γ-ray flux above energy E_γ, $J(>E_\gamma)$, to
lie within the region in Figure 1, bounded by upper and lower limits
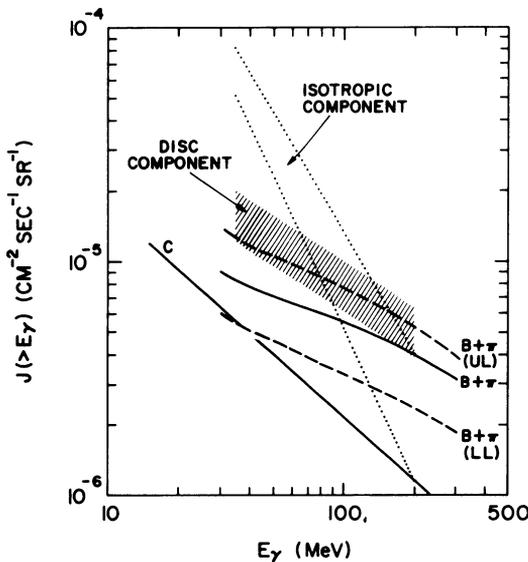

Figure 1. Integral fluxes in the directions of the
           galactic poles (see text).

designated by (UL) and (LL). Figure 1 also shows the data on the iso-
tropic and disk component (shown shaded) given by Fichtel et al. (1978).
All of these results are shown for b = 90°. The remaining curve, marked
C, shows the estimated flux of Compton γ-rays from an electron halo of
half-thickness h = 1.5 kpc. Such a component when added to the π+B
component will provide a better fit to the data, supporting the hypothesis
of a thin disk shaped electron halo. This result agrees with analysis
of the radio data by Illovaisky and Lequeux (1972) and Baldwin (1977).
However, the large uncertainties in both the γ-ray data and the theore-
tical calculations must be emphasized.

4. LONGITUDE DISTRIBUTION OF γ-RAYS AND THE NUCLEON HALO

Since cosmic ray nucleons do not produce measurable numbers of γ-rays
out of the gas disk of the galaxy, we must resort to indirect determina-
tion of their propagation based on their deduced radial distribution in
the galactic plane. This was the basic idea proposed in the analysis
of Stecker and Jones (1977). It is based on using a simple isotropic
diffusion model for cosmic ray propagation which seems reasonable if the
propagation region does not extend too far from the plane. For non-
isotropic diffusion with diffusion coefficients perpendicular and paral-
lel to the plane $D_\perp$ and $D_{||}$, the derived width of the diffusion disk (halo)
need only be scaled by the factor $(D_\perp/D_{||})^{1/2}$. Jones (1978) has considered
dynamical halos and finds that models with outflow may be replaced by
purely diffusive models with smaller effective halo thickness in analy-
zing the γ-ray results. This brings us back to the picture of a diffu-
sive propagation disk surrounded by an exodisk where outflow dominates
over diffusion.

It has been shown that if one analyzes the longitude distribution of
γ-ray emission in the plane, taking account of the presence of large
amounts of H_2 in the inner galaxy, the implied cosmic ray radial dis-
tribution closely resembles the distribution of supernovae (SN) in the
Galaxy, implying a galactic origin of cosmic rays (Stecker 1975). The
cosmic ray distribution is therefore source dominated on a scale of a
few kiloparsecs and we therefore expect the diffusion halo to be at
most a few kiloparsecs thick.

Stecker and Jones (1977) have made the conclusion more quantitative
by considering various models having boundaries such that at a distance
$L \simeq 2h$ from the plane the cosmic ray density drops to 0. The planes
defined by $|z| = L$ roughly correspond to the boundary between the
diffusion disk and the exodisk. Using SN and pulsar source distributions,
γ-ray emissivity distributions were computed for various values of L
and compared for probability of fit with the SAS-2 data. The results
varied from a ~ 30 to 40 percent probability of fit for L=2h=1 kpc to
a ~ 5 to 20 percent probability of fit for L=2h=3 kpc to a probability
fit of the order of a few percent for h = 2.5 kpc. Thus, within the
framework of the analysis it appears that the cosmic ray nucleon "halo"
has an effective half width h < 3 kpc. Measurements of the energy
spectrum of galactic γ-rays (Bennett et al. 1977, Kniffen et al. 1978)

indicate that perhaps up to ~ 50% of the radiation above 100 MeV may be from electron bremsstrahlung. However it is still reasonable to assume that the electrons and nucleons have the same source distribution. Using the results of the previous section which indicate a comparable width for the electron diffusion disk, it follows that the result for the nucleon diffusion disk h < 3kpc, should still be valid.
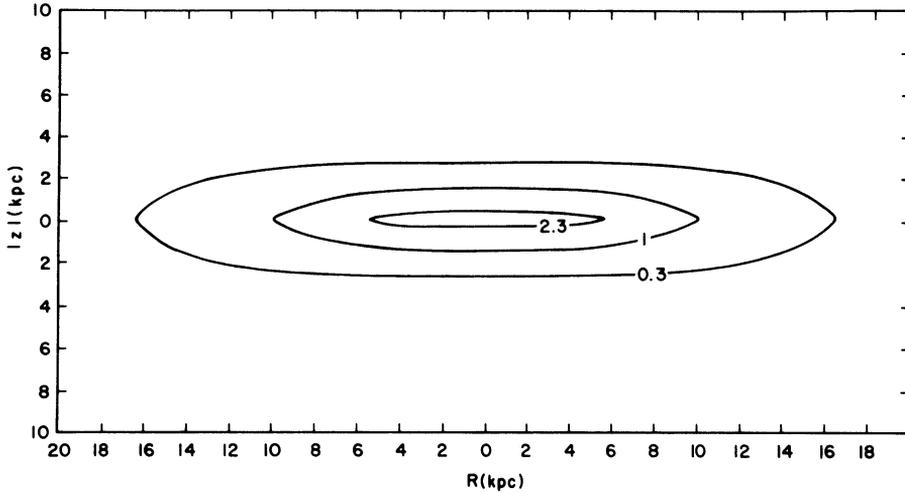

Figure 2. Relative column density of cosmic ray nuclei as seen from outside the Galaxy for the diffusion model of Stecker and Jones with L = 3 kpc.
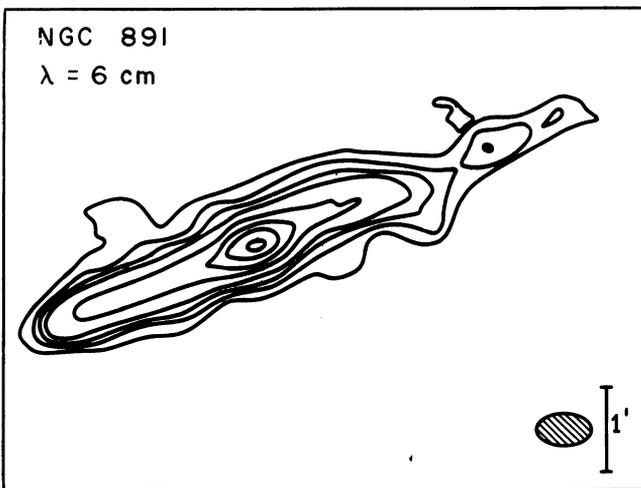

Figure 3. Contour plot of 6cm emission from NGC891, a galaxy similar to ours but with stronger radio emission and a strong nuclear emission component (Allen et al. 1978). Note the similarity to the halo model shown in Figure 2.
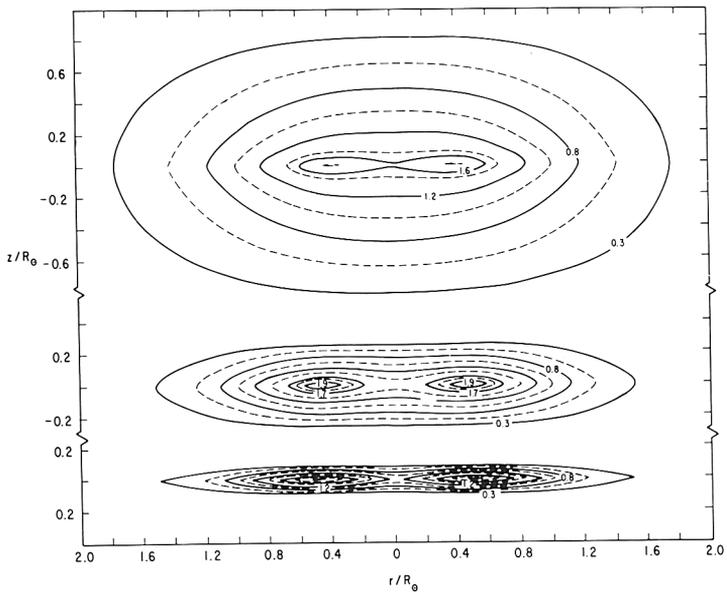
Figure 4.   Cross sectional contours of constant cosmic ray intensity
   in the r-Z plane for diffusion halos with L = 1,3 and 10 kpc. (See
   Stecker and Jones 1977)   The effect of the increased supernova
   density in the "Great Galactic Ring" at 5-6 kpc is seen in the
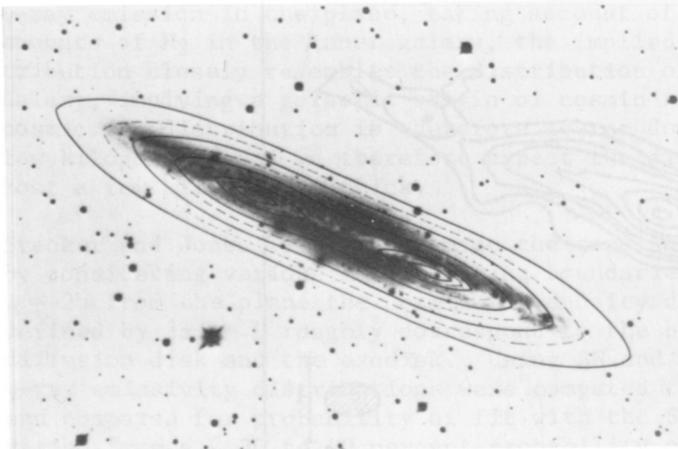   location of the peaks.   Scales are in units of 10 kpc.

Figure 5.   L = 3 kpc contours from Figure 4 superimposed on a photo-
   graph of NGC891 (courtesy Hale Observatories) to illustrate the
   scale of the halo models discussed in the text.

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DISCUSSION

Paul: The recent COS-B results show that many gamma-ray sources exist
in the Galaxy. Therefore it is quite premature to derive astrophysical
conclusions on the basis of pure diffuse-emission models, at least re-
garding large-scale characteristics of the Galaxy.

Stecker: Fichtel et al. have recently shown, in their analysis of the
moderate-latitude γ-radiation, that it is not made up of point sources
but is diffuse in nature. I believe that you also have recently shown
that there is an association of local γ-ray emission with molecular
clouds at moderate latitudes. The constancy of the γ-ray spectrum in
all parts of the Galaxy also argues for its primarily diffuse origin.
I therefore believe that there is strong support for the production of
most γ-rays in the inner Galaxy in molecular clouds as I suggested in
1969, and for the diffuse origin hypothesis.