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Gamma-Ray Evidence for a Galactic Halo

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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 definitions, 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 lifetime whereas nuclei do not. The electron halo is manifested through observations 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 interarm 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 nonthermal 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 measurements 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 $(1-2)x10^7$ 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 $(1-2)x10^7$ 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 cosmological 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 conclusions 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 contribution 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 $h = 2\pm2$ 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 hydrogen column density N_{HI+H_2} given by Jenkins (1977), the π°-decay production rate of Stecker (1970), and the bremsstrahlung production rate calculated 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

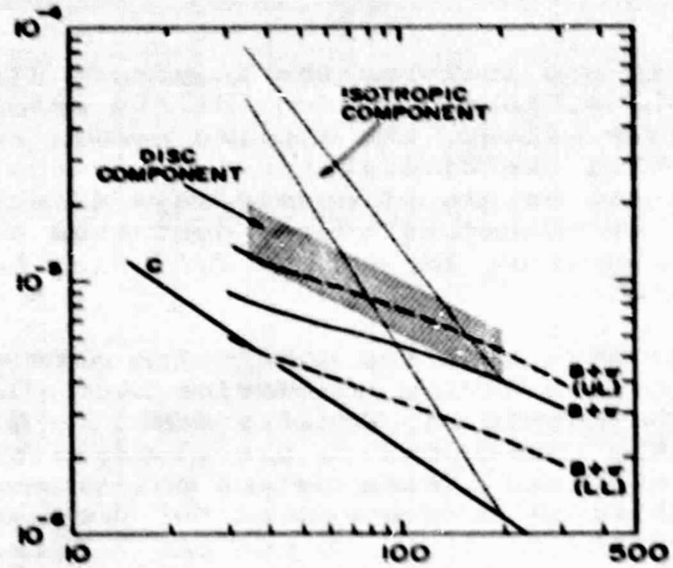

Figure 1. Integral fluxes in the directions of the galactic poles (see text).

designated by (UL) and (LL). Figure 1 also shows the data on the isotropic 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 theoretical 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 determination 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 parallel to the plane $D_\perp$ and $D_\parallel$, the derived width of the diffusion disk (halo) need only be scaled by the factor $(D_\perp/D_\parallel)^{\frac{1}{2}}$. 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 analyzing the γ-ray results. This brings us back to the picture of a diffusive 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 distribution 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 $L \sim 2h$ 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 $\sim$ 30 to 40 percent probability of fit for $L=2h=1$ kpc to a $\sim$ 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 $h \lesssim 3$ 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.

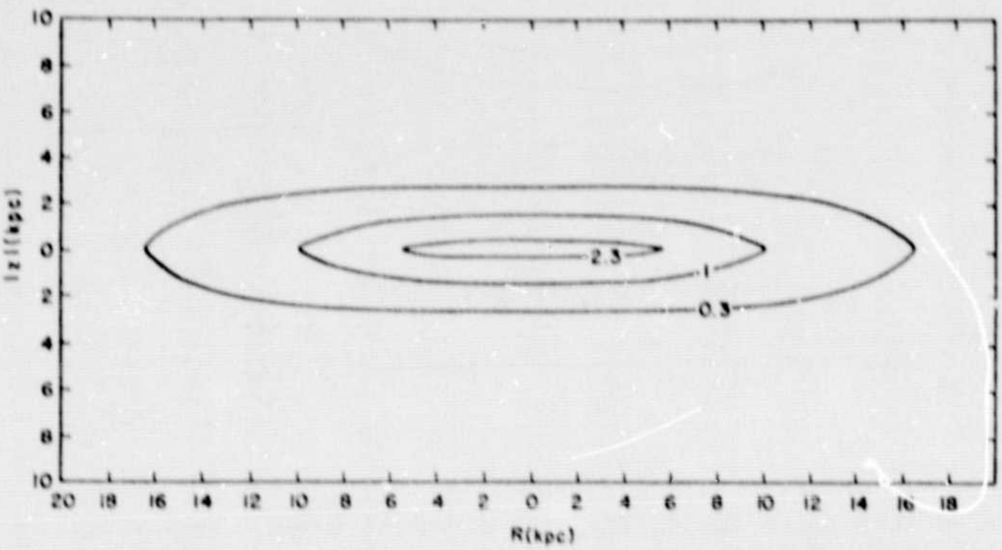

Figure 2. Relative column density of cosmic ray nuclei as seen from outside the Galaxy for the diffusion model of Stecker and Jones with L = 3 kpc.

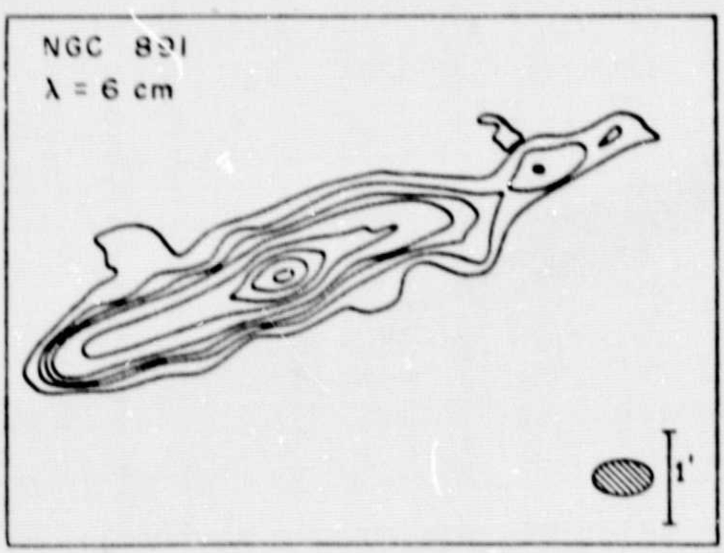

Figure 3. Contour plot of 6cm emission from NGC891, a galaxy similar to ours but with stronger radio emission and a strong nuclear emission component (Allen et al. 1978). Note the similarity to the halo model shown in Figure 2.

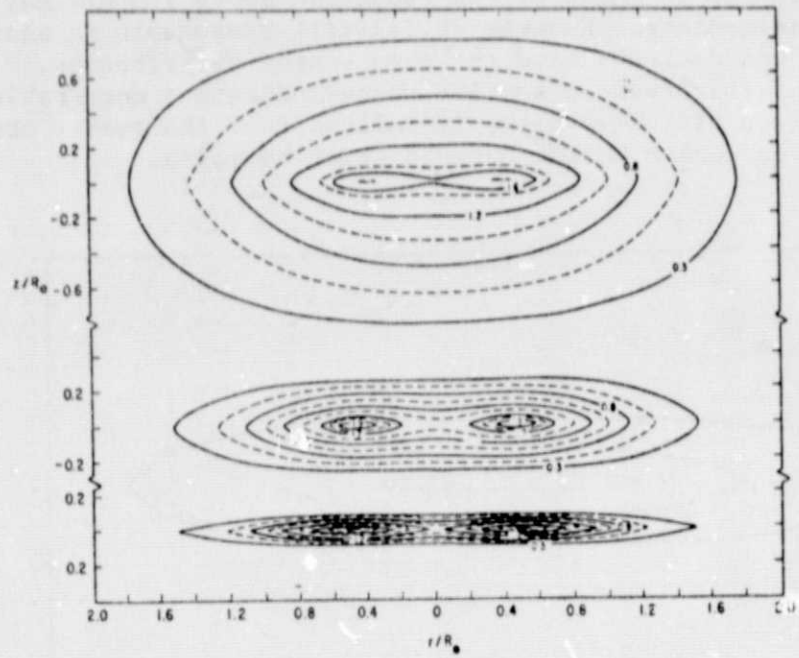

Figure 4. Cross sectional contours of constant cosmic ray intensity in the r-Z plane for diffusion halos with L = 1,3 and 10 kpc. (See Stecker and Jones 1977) The effect of the increased supernova density in the "Great Galactic Ring" at 5-6 kpc is seen in the location of the peaks. Scales are in units of 10 kpc.

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

REFERENCES

Allen, R. J., Baldwin, J. E. and Sancisi, R.: 1978, *Astron. and Astrophys.* *62*, 397.
Badhwar, G. D. and Stephens, S. A.: 1977, *Ap. J.* *212*, 494.
Baldwin, J.: 1977 in *The Structure and Content of the Galaxy and Galactic γ-Rays* (Proc. Greenbelt, Int'l. Symp. NASA CP-002, U. S. Govt. Printing Office, Washington) p. 189.
Bennett, K. et al. (CARAVANE Collaboration) in *Recent Advances in γ-Ray Astronomy* (Proc. Frascati Int'l. Symp. ESA-SP-124; ESA Publications Branch, Noordwijk) p. 83.
Fichtel, C. E., Hartman, R. C., Kniffen, D. A., Thompson, D. J., Bignami, G. F., Ögelman, H., Özel, M. F. and Tümer, T.: 1975, *Ap. J.* *198*, 163.
Fichtel, C. E., Hartman, R. C., Kniffen, D. A., Thompson, D. J., Ögelman, H. B., Özel, M. E. and Tümer, T.: 1977, *Ap. J.* *217*, L9.
Fichtel, C. E., Simpson, G. A. and Thompson, D. J.: 1978, *Ap. J.* *222*, in press.
French, D. K. and Osborne, J. L.: 1976, *Mon. Not. R. Astr. Soc.* *177*, 569.
Garcia-Munoz, M., Mason, G. M. and Simpson, J. A.: 1977, *Ap. J.* *217*, 859.
Goldstein, M. L., Ramaty, R. and Fisk, L. A.: 1970, *Phys. Rev. Lett.* *24*, 1193.
Gordon, M. A. and Burton, W. B.: 1976, *Ap. J.* *208*, 346.
Heiles, C.: 1976, *Ap. J.* *204*, 379.
Ilovaisky, S. A. and Lequeux, J.: 1972, *Astr. and Ap.* *20*, 347.
Ipavich, F. M.: 1975, *Ap. J.* *196*, 107.
Jenkins, E. B.: 1977, in *The Structure and Content of the Galaxy and Galactic γ-Rays* (Proc. Greenbelt, Int'l. Symp. NASA CP-002; U. S. Govt. Printing Office, Washington) p. 215.
Jokipii, J. R.: 1976, *Ap. J.* *208*, 900.
Jones, F. C.: 1978, *Ap. J.* *222*, in press.
Kniffen, D. A., Bertsch, D. L., Morris, D. J., Palmeira, R. A. R., and Ras, K. R.: 1978, *Ap. J.* in press.
Ormes, J. and Freier, P.: 1978, *Ap. J.*, in press.
Owens, A. J. and Jokipii, J. R.: 1977, *Ap. J.* *215*, 677.
Parker, E. N.: 1977, in *The Structure and Content of the Galaxy and and Galactic γ-Rays* (Proc. Greenbelt, Int'l. Symp. NASA CP-002; U. S. Govt. Printing Office, Washington) p. 783.
Roberts, W. W., Jr.: 1977, in *The Structure and Content of the Galaxy and Galactic γ-Rays* (Proc. Greenbelt Int'l. Symp. NASA CP-002; U. S. Govt. Printing Office, Washington) p. 119.
Schlickeiser, R. and Thielheim, K. O.: 1977, *Ap. and Space Sci.* *47*, 415.
Stecker, F. W.: 1970, *Ap. and Space Sci.* *6*, 377.
Stecker, F. W.: 1975, *Phys. Rev. Lett.* *35*, 188.
Stecker, F. W.: 1977, *Ap. J.* *212*, 60.
Stecker, F. W.: 1978a, *Nature*, in press. (NASA TM 78114)
Stecker, F. W.: 1978b, *Ap. J.* *223*, in press. (NASA TM 78045)
Stecker, F. W. and Jones, F. C.: 1977, *Ap. J.* *217*, 843.
Webster, A.: 1975, *Mon. Not. R. Astr. Soc.* *171*, 243.
Worrall, D. M.: 1977, Ph.D. Thesis, University of Durham.
Worrall, D. M. and Strong, A. W.: 1977, *Astron. and Ap.* *57*, 229.

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