FEASIBILITY FOR EGRET DETECTION

OF ANTIMATTER CONCENTRATIONS IN THE UNIVERSE

R. C. Hartman
NASA/Goddard Space Flight Center
Greenbelt, MD 20771

INTRODUCTION

Although the Grand Unified Theories of elementary particle dynamics have to some extent reduced the aesthetic attraction of matter-antimatter symmetry in the Universe, the idea is still not ruled out. Although first introduced by Alfven(1965), most of the theoretical development related to gamma-ray astronomy has been carried out by Stecker, who has proposed (Stecker, Morgan and Bredekamp, 1971) matter-antimatter annihilation extending back to large redshifts as a possible explanation of the apparently extragalactic diffuse gamma radiation. Other candidate explanations have also been proposed, such as superposition of extragalactic discrete sources.

Clearly, the existence of significant amounts of antimatter in the universe would be of great cosmological importance; its detection, however, is not simple. Since the photon is its own antiparticle, it carries no signature identifying whether it originated in a matter or an antimatter process; even aggregates of photons (spectra) are expected to be identical from matter and antimatter processes. The only likely indicator of the presence of concentrations of antimatter is evidence of its annihilation with normal matter, assuming there is some region of contact or overlap.

The EGRET telescope on the Gamma Ray Observatory, with a substantial increase in sensitivity compared with earlier high energy gamma-ray telescopes, may be able to address this issue. This paper is a preliminary consideration of the feasibility of using EGRET in such a search for antimatter annihilation in the Universe.

ANNIHILATION PROCESSES AND THEIR DETECTION

Two processes are available for study; annihilation between electrons and positrons, with an energy release of about 1 MeV per pair, and annihilation between nucleons and antinucleons, with an energy release of nearly 2 GeV per nucleon/antinucleon pair. Although the electron-positron annihilation should produce the well-known 511 keV line, there are observational problems which reduce the likelihood of success in its use for cosmological observations. First, the half-MeV line forms its own unavoidable background in any instrument which can observe

it. In addition, positron annihilation is likely to be present in a wide range of astrophysical settings, including stellar flares, supernovae ejecta and active galactic nuclei, even if antimatter does not form a significant portion of the Universe.

Nucleon/antinucleon annihilation is more complicated than that of electrons and positrons. Even annihilation of a nucleon-antinucleon pair at rest produces several particles; most of these are pions, including both charged and neutral. The only significant production of photons in this process is via the decay of the neutral pions. Although the π° decay is two-body, the decaying pions have energies comparable to their rest mass, so the photon line is smeared out into a broad hump peaked at 68 MeV, as shown in Figure 1.

Gamma-ray detectors in this energy range are largely free of internal background, so it is necessary to contend only with astronomical sources of background, which are discussed later.
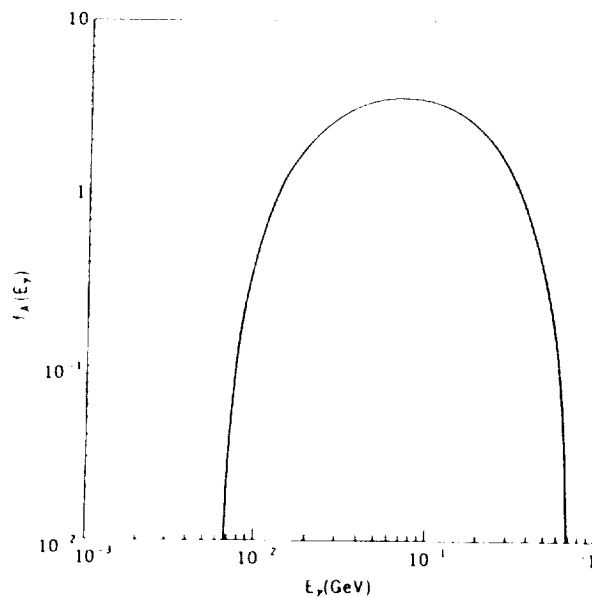
Figure 1 - The normalized gamma-ray spectrum from proton-antiproton annihilation.

WHERE COULD ANTIMATTER BE CONCENTRATED?

There is strong evidence that no significant amount of antimatter exists within our own galaxy, nor anywhere within the Local Group of galaxies. Such a concentration would be clearly visible in high energy gamma radiation, but has not been identified by the SAS-2 or COS-B instruments. Bel and Martin (1975) have shown that it is not possible for individual

galaxies to be randomly divided into matter galaxies and antimatter galaxies, since the annihilation radiation resulting from galaxy collisions throughout the universe would produce a gamma-ray background two to three orders of magnitude greater than that seen by SAS-2. Similarly, Harwitt (1989) has shown that the IRAS ultraluminous galaxies cannot all be due to collisions between matter and antimatter galaxies. Thus we are forced to consider structures as large as galaxy clusters or even superclusters as possible domains of matter and antimatter. It is assumed here that such domains must be separated by voids in the distribution of luminous matter; this seems reasonable, since the energy released in annihilation at the domain boundaries should be quite adequate to prevent the formation of matter condensations.

Figure 2 (on the last page of these proceedings) shows the northern sky distribution of galaxy clusters, sorted into superclusters, out to a redshift z of 0.1. The definition of a supercluster is rather loose; the groupings depend upon somewhat arbitrary assumptions regarding the minimum physical separation assumed between associated clusters. The 48 superclusters shown in Figure 2 were identified recently by West (1989) using a minimum distance between associated clusters of 25 Mpc. About half of the superclusters shown contain from 3 to 13 galaxy clusters; the other half each contain only a pair of clusters. Some of these pairs are quite closely spaced and almost certainly associated, but others would not be linked were a slightly smaller distance requirement used. In the sample used by West, which includes all 286 clusters in the northern Abell catalog for which redshifts of less than 0.1 have been measured, only about 65% of the galaxy clusters were found to lie within superclusters according to his criteria. Other authors (e.g. Bahcall and Soneira, 1986) have used different selection criteria, with correspondingly different (but not inconsistent) results.

Figure 3 (on the last page of these proceedings) shows the resulting sky distribution if the non-associated clusters are included. The added 99 clusters are not within 25 Mpc of any other cluster in the sample. Note that many of the apparently empty regions seen in Figure 2 are now filled in.

Figures 2 and 3 do not give any information about the distances of the clusters; Figure 4 (last page of these proceedings) shows the same clusters, separated into three equal redshift-intervals, to indicate crudely the distance to each cluster. As would be expected, there are few superclusters in the closest distance interval, and those have very substantial angular size (up to 25 degrees).

It is important to note that, even when all of the clusters are considered, there are regions of the sky which appear empty. These might be considered as potential boundaries between matter/antimatter domains, and therefore as possible sites of

annihilation. However, several cautions must be stated in this connection. First, redshift measurements are not available for all galaxy clusters out to z=0.1, so there may actually be clusters in some of the regions which appear empty here. Second, and probably more important for the topic studied here, the fraction of luminous mass in the Universe which falls within clusters has been estimated by various authors (e.g., Bahcall and Soneira, 1984) to be within the range 10-25%. The remainder is in the isolated galaxies referred to as field galaxies. Thus the absence of clusters and superclusters in a region does not necessarily imply the absence of all luminous matter.

Another very striking way of looking at the large-scale distribution of matter in the Universe is that of Kirshner et al.(1981) and deLapparent et al.(1986). Figure 5(a) hows the positions of all galaxies brighter than m_B = 15.5 out to a redshift of about 0.05, for a 6 degree slice in declination, 9 hours wide in right ascension. The important feature here is obvious: much of the area of the plot is essentially empty of observable galaxies. Included in this diagram is the Coma cluster, which turns out to be merely the densest portion of a network of apparent filaments. Examination of the three-dimensional structure near this slice indicates that, rather than a true filamentary connection, the galaxy distribution forms a series of nearly empty bubbles. Note that in Figure 5 there is no obvious separation of the galaxy shells into structures which might be matter and antimatter. However, this slice covers only a small fraction of the sphere extending out to z=0.1.

HOW MUCH ANNIHILATION RADIATION SHOULD THERE BE?

We examine an idealized geometry, shown in Figure 6, with semi-infinite regions of matter and antimatter separated by an overlap region in which annihilation occurs. As an illustration, several parameters are defined with minimal justification.

For gas density, a value of 4×10^{-8} cm^{-3} (pure hydrogen or antihydrogen) is used; this is only about 1% of the closure density for H_0 = 60 km s^{-1} Mpc^{-1}. In the boundary layer, this density is equally divided between matter and antimatter.

There is no clear guideline to a choice of temperature; it is a crucial parameter, however, because the annihilation rate is temperature dependent. In particular, Stecker (1971) has shown that, at a temperature of a few thousand degrees (where hydrogen becomes largely ionized), the annihilation rate drops precipitously, by about three orders of magnitude. Initially, a temperature of 10^5 degrees is utilized here, but the effect of other choices will be examined later.
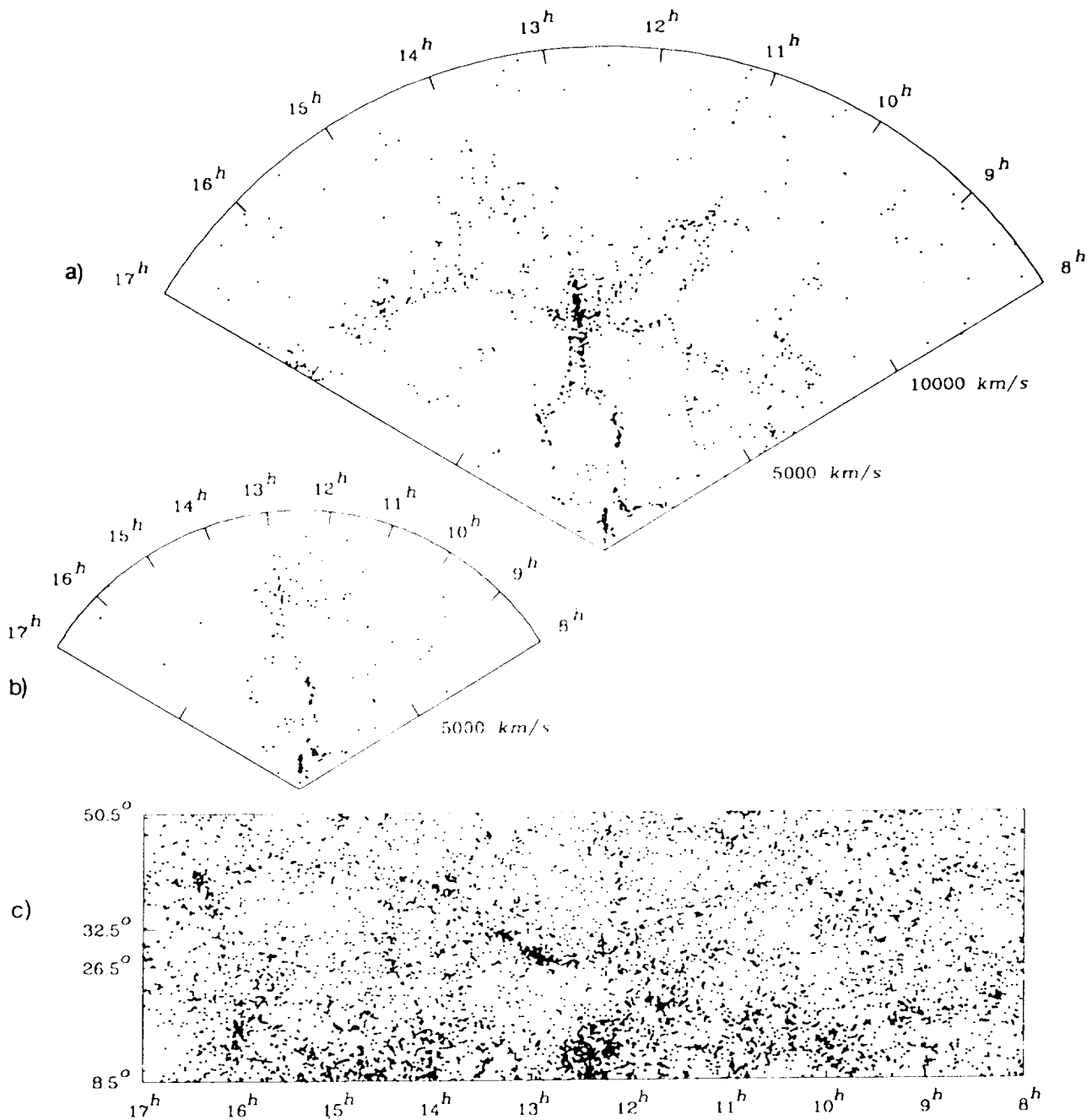
Figure 5 (from de Lapparent et al., 1986) - (a) Map of observed velocity plotted vs. right ascension in the declination wedge $26.5°-32.5°$, for 1061 objects with $m_B \leq 15.5$ and velocity $\leq 15,000$ km s^{-1}. (b) same as (a), but for 182 galaxies with $m_B \leq 14.5$ and velocity $\leq 10,000$ km s^{-1}. (c) Projected map of 7031 objects with $m_B \leq 15.5$.
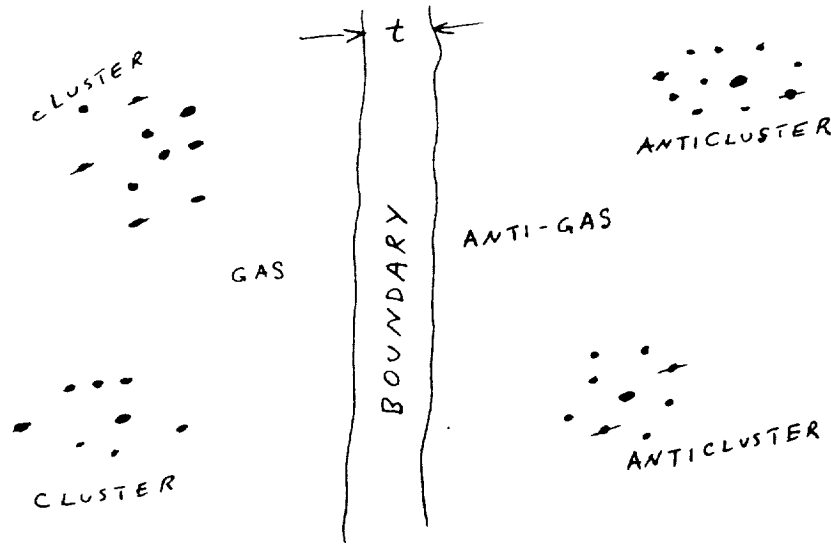
Figure 6 - Idealization of the boundary between a matter domain and an antimatter domain.

If the matter and antimatter are permitted to intermix freely at the boundary, its thickness t depends upon the mean free path for annihilation, which is given by (Stecker and Puget, 1972) $t = 2.8/(n\sigma)$. Using the parameters mentioned above, this leads to a boundary layer thickness of 450 Mpc, which is more than an order of magnitude greater than the typical distance between superclusters. Reducing the temperature to 10^4 K and increasing the gas density by an order of magnitude (about the maximum allowable) reduces the boundary layer thickness to 3 Mpc, which seems reasonable.

The annihilation gamma-ray intensity is given by:

$$I = \frac{1}{4\pi} \int n_p \, n_{ap} \, \langle v\sigma \rangle \, dl$$

$$= 10^{-14} \, n_p \, n_{ap} \, L \, T_6^{-0.5} \, cm^{-2} \, s^{-1} \, sr^{-1} \qquad (1)$$

where n_p and n_{ap} are the number densities of the two components, T_6 is the temperature in millions of degrees, and L is the line of sight distance through the boundary layer. $\langle v\sigma \rangle$ is the annihilation gamma-ray production rate for unit densities and for the specific temperature selected, derived from Stecker(1971), which scales with temperature as $T^{-0.5}$ over the range 10^4 K to 10^{11} K.

Inserting into Equation 1 the temperatures and densities discussed above leads to gamma-ray intensities of 0.02 to $0.07/(cm^2 \, s \, sr)$. Emission this bright would have been easily visible in the SAS-2 and COS-B instruments, but was not seen;

this forces us to conclude that, if antimatter does exist within domains in the universe, matter and antimatter cannot be freely mixing at the domain boundaries.

One possibility for inhibiting the mixing would be turbulent pressure stimulated by the annihilation itself. In addition to the neutral pions produced in nucleon-antinucleon annihilation, charged pions are also produced. These decay quickly, resulting in relativistic electrons and positrons in addition to neutrinos. The electrons and positrons streaming away from the boundary may, in the presence of a magnetic field, be able to generate sufficient turbulent pressure to inhibit the flow of gas toward the interface, leading to substantially lower gas densities in the annihilation region. A complex computation would be required to determine how effective such a process might be.

A rough estimate of what density is permitted by the observations can be made by assuming that an intensity of 10^{-4} cm^{-2} s^{-1} sr^{-1} (> 100 MeV) would have been detectable by SAS-2 away from the galactic plane. For a temperature of 10^6 K and a boundary layer thickness of 1 Mpc, a density of about 6×10^{-8} cm^{-3} (equally divided between matter and antimatter) would be permitted. If 10^4 K and 10 Mpc are chosen instead, the density in the boundary region can be only about 6×10^{-9} cm^{-3}.

OBSERVING EXTRAGALACTIC DIFFUSE HIGH ENERGY GAMMA RAYS

The first problem in making detailed observations of extragalactic gamma radiation is development of an accurate model of the high-latitude emission from our own galaxy. This emission arises from interactions between galactic cosmic rays, both electrons and nuclei, and several components of the interstellar medium. Some of these components, such as atomic hydrogen, are reasonably well defined. Densities of cosmic ray electrons and nuclei, however, are known with confidence only in the solar neighborhood. Gamma-ray observations from SAS-2 and COS-B have shown that there are cosmic rays throughout the Galaxy; however, the details of their distribution in the Galaxy are not well determined.

As in other wavelength bands, extragalactic gamma-ray observations must be made through one to several half-thicknesses of the disk of the Galaxy. Indeed, the SAS-2 discovery of the apparently extragalactic gamma radiation around 100 MeV was made by comparing gamma-ray fluxes at high galactic latitudes with line-of-sight integrals of various components of the interstellar medium. As illustrated in Figure 7, the extragalactic gamma-ray component is the flux obtained by extrapolating to zero the line-of-sight integral of another component. Even at high galactic latitudes, the galactic contribution to the observed gamma-ray intensity is in general quite substantial.
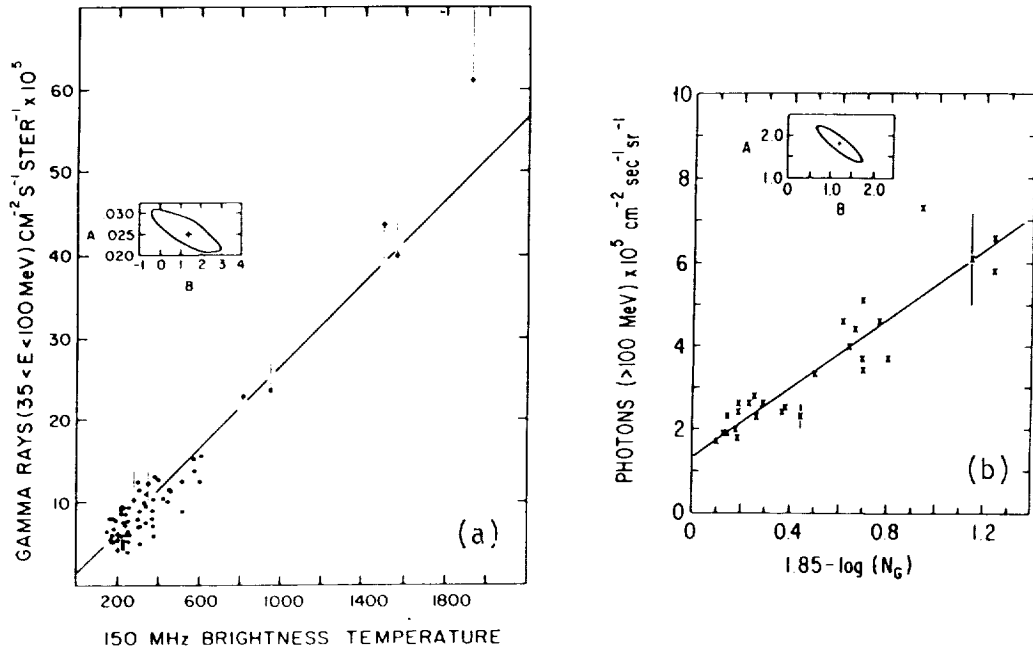
Figure 7 - (a) (from Fichtel, Simpson and Thompson 1978) Gamma-ray intensity (35 - 100 MeV) vs. 150 MHz brightness temperature. (b) (from Thompson and Fichtel 1982) Gamma-ray intensity (E>100 MeV) vs. the function 1.85-log(galaxy counts per square degree) for galactic latitudes |b|>10°.

In the SAS-2 discovery of the extragalactic high energy gamma radiation, the relatively poor statistical weight of the gamma-ray observations was a severe limitation. The EGRET telescope, with a factor of 15 better sensitivity and in principal a much longer lifetime for such observations, should greatly reduce those statistical limitations. Furthermore, complete high-latitude observations of atomic hydrogen are now available (Heiles and Habing 1974; Colomb, Poppel and Heiles 1980), and observations of CO, the tracer for molecular hydrogen, are underway at high galactic latitudes (Stacy 1989). It seems likely that, unless the cosmic ray distribution at high latitudes is more "clumpy" than expected, a relatively accurate subtraction of the galactic high energy gamma-ray background will be possible. It is less certain that it will be possible to obtain useful spectra, in sky regions as small as a few square degrees, for the extragalactic radiation remaining after subtraction of the galactic component.

WHAT SHOULD WE LOOK FOR?

From the considerations given above, it is clear that matter-antimatter boundaries *might* be detectable with reasonable values for their width and density. Since there appears to be no way to put useful lower limits on those parameters, it is not true that domain boundaries *must* be observable. A search must therefore be carried out, but negative results probably would not rule out the existence of antimatter domains in the Universe.

It appears that a likely approach would be to search for correlation between the angular density of luminous matter (galaxies and clusters) and the observed gamma-ray intensity after subtraction of galactic background. A *negative* correlation would indicate that the optically empty regions are producing more gamma rays than the luminous matter, and would therefore support the idea of a domain structure of matter and antimatter in the Universe. Additional very strong support would come from a demonstration that the spectrum of the gamma radiation from the apparently empty regions is similar to that shown in Figure 1, very different from the spectrum of gamma rays generated within our own galaxy or that observed from active galactic nuclei. As mentioned above, however, it is not certain that the spectrum obtained after galactic background subtraction would be sufficiently accurate to make such a determination.

REFERENCES

Alfven, H. 1965, *Rev. Mod. Phys.*, **37**, 652.

Bahcall, N. A., and Soneira, R. M. 1984, *Ap. J.*, **277**, 27.

Bel, N., and Martin, P. 1975, *Astr. Ap.*, **46**, 455.

Colomb, F. R., Poppel, W. G. L., and Heiles, C. 1980, *Astr. Ap. Suppl.*, **40**, 47.

Fichtel, C. E., Simpson, G. A., and Thompson, D. J. 1978, *Ap. J.*, **222**, 833.

Harwitt, M. 1989, *Ap. J.*, **347**, 688.

Kirshner, R. P., Oemler, A., Schecter, P. L., and Shectman 1981, *Ap. J. (Letters)*, **248**, L57.

de Lapparent, V., Geller, M. J., and Huchra, J. P. 1986, *Ap. J. (Letters)*, **302**, L1.

Stacy, J. G. 1989, private communication.

Stecker, F. W., Morgan, D. L., and Bredekamp, J. 1971, *Phys. Rev.*, **27**, 1469.

Stecker, F. W. 1971, *Cosmic Gamma Rays* (NASA SP-249).

Stecker, F. W., and Puget, J. L. 1972, *Ap. J.*, **178**, 57.

Thompson, D. J., and Fichtel, C. E. 1982, *Astr. Ap.*, **109**, 352.

West, M. J. 1989, *Ap. J.*, **347**, 610.

DISCUSSION

R.J. Slobdrian:

There is also speculation on the existence of strings of very high density matter, then, of course, one may have similar strings of antimatter, and upon collision they would produce very strong sources of radiation.
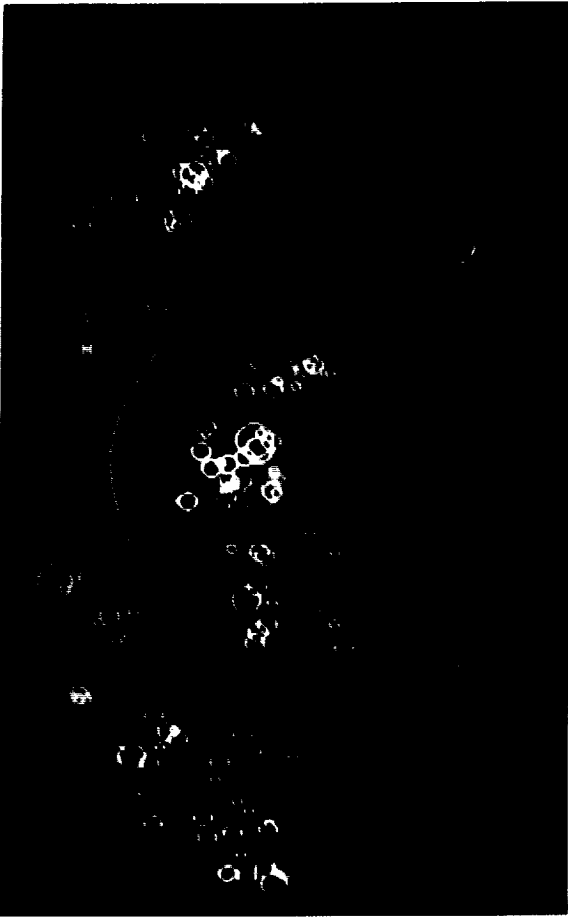
Bob Hartman:

Clearly, we will be alert to unexpected features in the diffuse radiation. Unfortunately, there is no indication of where such features should occur, or even what their angular scale might be. If they are to be separable from point sources, they would probably have to be several degrees in size.
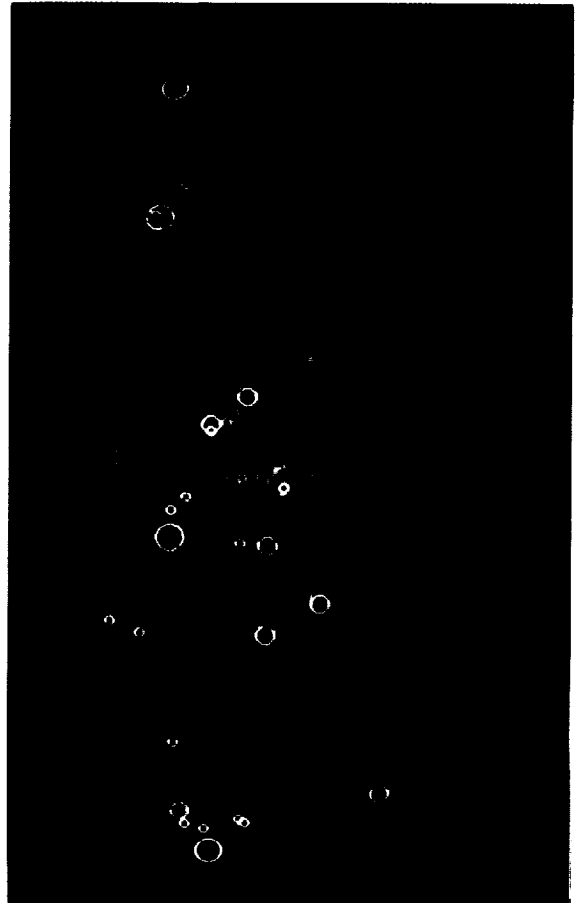
(3)

(2)

(4)

Figure 2. Aitoff plot in celestial coordinates of Abell clusters (z < 0.1) assigned to superclusters by West(1989). The circle sizes indicate Abell richness class (0 - 5). Member clusters in a supercluster are shown in the same color; however, each color is used to represent several well-separated superclusters.

Figure 3. Same as Figure 2, but showing in white the Abell clusters which are not within a supercluster (more than 25 Mpc from all other clusters).

Figure 4. Abell clusters with z < 0.1, color coded into three redshift intervals: yellow, 0.000 - 0.033; orange, 0.033 - 0.067; red, 0.067 - 1.000.

344