EVIDENCE AGAINST THE SCIAMA MODEL OF RADIATIVE DECAY OF MASSIVE NEUTRINOS¹

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ABSTRACT
We report on spectral observations of the night sky in the band around 900 Å where the emission line in the Sciama model of radiatively decaying massive neutrinos would be present. The data were obtained with a high-resolution, high-sensitivity spectrometer flown on the Spanish satellite MINISAT. The observed emission is far less intense than that expected in the Sciama model.

Subject headings: cosmology: observations — diffuse radiation — ultraviolet: general

1. INTRODUCTION
Relic neutrinos, if massive, could contribute significantly to the density of the universe, and, if appropriately concentrated, could explain puzzling characteristics of luminous matter in galaxies. Melott (1984) suggested that if these particles were radiatively decaying, they could be responsible for the sharp hydrogen ionization edges seen in many galaxies, and that this decay would not violate existing observational data if the decay energy was somewhat greater than 13 eV and the lifetime for decay was about $10^{24}$ s. In a subsequent paper, Melott, McKay, & Ralston (1988) showed that this idea was consistent with observations of star formation, galaxy formation and morphology, and other phenomena. Subsequently, Sciama and collaborators in an extensive set of papers (Sciama 1990, 1993, 1995, 1997a, 1997b, 1998; Sciama, Persic, & Salucci 1993) showed that if the decay lifetime was an order of magnitude less than that suggested by Melott, his theory could explain a large number of otherwise puzzling astronomical phenomena, including the ionization state of the intergalactic medium and the anomalous ionization of the interstellar medium (ISM) in our own Milky Way. Although massive neutrinos cannot be contemplated within the framework of the standard model of particle physics, they can be accommodated in the supersymmetric extensions of the standard model, especially if $R$ parity is broken (cf. Gato et al. 1985; Bowyer et al. 1995). Recent observational and experimental results suggest that they do, in fact, have mass (Fukuda et al. 1998a, 1998b; Athanassopoulos et al. 1998a, 1998b).

A number of searches have been made for evidence of radiatively decaying massive neutrinos in clusters of galaxies. Davidsen et al. (1991) severely constrained the parameter space available for these particles through observations of the cluster of galaxies Abell 665, and Fabian, Naylor, & Sciama (1991) obtained similar results from a study of the cluster of galaxies surrounding the quasar 3C 263. However, Sciama et al. (1993) and Bowyer et al. (1995) have shown that these observations do not rule out the Sciama scenario.

An all-pervading neutrino flux in the Galaxy at a wavelength near the ionization limit of hydrogen would be difficult to observe because of absorption by the ISM. However, Bowyer et al. (1995) pointed out that this flux would be observable from Earth orbit in several well-defined directions where the density of the ISM is extremely low. An observational complexity which could complicate these measurements is emission from an upper-atmosphere oxygen recombination feature at 911 Å (Chakrabarti et al. 1983).

In this paper we report results of spectral observations made in the region $\leq 912$ Å, where the radiation in the Sciama scenario would be present, and compare the data obtained with the flux expected.

2. OBSERVATIONS
The observations were made with an extreme-ultraviolet (EUV) spectrometer covering the bandpass from 350 to 1100 Å, which was specifically designed for studies of diffuse emission. The instrument (the Espectrógrafo Ultravioleta de Radiación Difusa [EURD]) is capable of providing measurements of the diffuse UV background that are over a 100 times more sensitive than existing measurements in this bandpass, with a spectral resolution of about 6 Å. The instrument is described in detail by Bowyer, Edelstein, & Lampton (1997).

The instrument was flown on board the Spanish satellite MINISAT-01, launched on 1997 April 21. The spacecraft is in a retrograde orbit with an inclination of 151° and is at an altitude of 575 km. The spectrometer continuously views the anti-Sun direction. Details of the spacecraft and the EURD observational parameters are provided in Morales et al. (1996).

We examined EURD data in the 890–915 Å bandpass in an attempt to detect the emission which would be present if the Sciama scenario was operative. Data from the spectrometer were typically collected over the entire nighttime portion of the orbit. Higher count rates are always experienced at spacecraft sunrise and sunset due to geocoronal effects, but deep night intensities are typically constant and

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low. For the search for radiation from the Sciama scenario, we sorted the data to exclude all sunrise and sunset data and all other data associated with high backgrounds. Given the low in-flight count rate and the absolute fixed electronics dead time of 100 $\mu$s photon$^{-1}$, dead time corrections were about 1% and were therefore ignored.

The EURD spectrograph employs a number of vetoes to reduce unwanted background and to permit evaluation of those background events which cannot be otherwise eliminated (Bowyer et al. 1997). The detector is surrounded by an anticoincidence shield, and all counts triggering this shield (about 20%) are rejected. Remaining internal background components include charged particles that are missed by the anticoincidence system, Compton-scattered $\gamma$-rays, and radioactivity within the detector and in the spacecraft. An additional background is produced by photons scattered by the grating onto the detector. This scattered emission is mostly a continuum arising from the wings of the zero and first order of the hydrogen Ly$_\alpha$ line, whose peaks were designed to fall beyond the ends of the detector.

The entrance aperture of the instrument has a filter wheel with three positions: Open, Closed, and a MgF$_2$ filter. The Open position provides spectral data plus backgrounds. The Closed position gives an estimate of the internal background, and the MgF$_2$ filter position gives an estimate of the scattered radiation. Observations were carried out sequentially with each of these apertures; the complete cycle time was 90 s.

We corrected the deep night spectral data for backgrounds using the MgF$_2$ and Closed apertures. We summed the background-corrected data in the 890–915 Å band as a function of time. We included data to 915 Å to ensure that all counts shortward of 912 Å were included in the sample given the spectral resolution of the instrument. In some neutrino decay scenarios, two lines will be produced whose relative intensities are uncertain. However, the sum of these two lines is the key parameter to be measured, and in the Sciama scenario these lines will be separated by 0.2 eV, or 13 Å at 900 Å. Hence the flux from both of these lines will be included in the data reported here. For this study we utilized data obtained between 1997 June 18 and 1998 June 29. Data were regularly obtained over most of this period, with occasional gaps because of spacecraft problems or instrument shutdowms. Data were summed over 10 day intervals, providing typically about 3500 counts, to obtain good counting statistics.

Unfortunately, in regard to our search for the Sciama line, oxygen recombination radiation was substantial at the altitude of MINISAT even in the anti-Sun view direction. A spectrum of the radiation detected around 912 Å is shown in Figure 1. This spectrum shows a profile that is consistent with the line shape obtained by Feldman et al. (1992) given the resolution of this instrument. Just longward of 912 Å the spectrum is dominated by the Lyman series lines of geocoronal hydrogen (Lopez-Moreno et al. 1998). Both the oxygen recombination feature and the Lyman series lines of hydrogen vary in time; the data shown in Figure 1 are from a period when the oxygen recombination radiation was more pronounced.

We determined the EURD counts-to-flux conversion factor in the region around 800 Å using an in-flight calibration strategy based on simultaneous EUV observations of the Moon with EUVE and EURD (Flynn et al. 1998), and, longward of 912 Å, by fits to stellar spectra (Morales et al. 1999). It is estimated that this calibration is good to ±20% in the band around 912 Å because of the quality of the fit to stellar spectra. This in-flight calibration yields a conversion of $6.5 \times 10^4$ photons cm$^{-2}$ sr$^{-1}$ counts$^{-1}$ at 912 Å; this is within a factor of 3 of the preflight calibration (Bowyer et al. 1997). This difference is easily understood as being the result of the degradation of the detector photocathode during the almost 2 year time period between the laboratory calibration and in-orbit operation. The resulting fluxes are shown in Figure 2. These fluxes are the total fluxes obtained in this bandpass, uncorrected for any Lyman series emission as seen in Figure 1.

The expected emission in the Sciama scenario can best be considered in two parts. The first is produced in the local interstellar cloud (LIC) that surrounds the Sun; this emission is intermixed with absorption. The second component
is emission from beyond the LIC which is absorbed by this cloud.

Formally, the emission is given by the relation

\[
I(l) = B + \frac{R_{\text{prod}}}{4\pi n_0 \sigma} \left\{ 1 - \exp \left[ -n_0 ad_{cl}(l) \right] \right\} + \frac{R_{\text{prod}}[d_{cl}(l) - d_{cl}]}{4\pi} \exp \left[ -n_0 d_{cl} \right],
\]

where we have included a background, \(B\) (which could be due to anything but is mostly due to oxygen recombination radiation); \(R_{\text{prod}}\) is the photon production rate; \(n_0\) is the density of the LIC; \(\sigma\) is the effective ISM cross section for absorption (Rumph, Bowyer, & Vennes 1994); \(d_{cl}\) is the distance to the cloud edge; and \(d_c\) is the distance to the edge of the neutral free region. The symbol \(l\) indicates variation with ecliptic longitude. The most recent (small) revision of the theory (Sciama 1998) requires a photon production rate of \((2 \pm 1) \times 10^{16} \text{ s}^{-1} \text{ cm}^{-3}\).

We have used the model of Redfield & Linsky (1999) for data on the LIC. This is a three-dimensional model which is based on ISM absorption features in the spectra of nearby stars obtained with \textit{HST}, \textit{EUVE}, and ground-based telescopes. Minimum hydrogen columns in the plane of the ecliptic in this model are \(~2.5 \times 10^{16} \text{ cm}^{-2}\), maximum columns are \(~2.5 \times 10^{18} \text{ cm}^{-2}\).

In the region beyond the LIC, Welsh, Crido, & Lallement (1998) used high-resolution optical spectroscopy to determine the amount of ISM sodium in the line of sight to stars within 300 pc of the Sun. They found that the ISM is essentially free of neutral gas out to more than 70 pc in most directions. Sfeir et al. (1999) have obtained an extensive set of sodium absorption data and have modeled the extent of this ionized region, or Local Bubble. We have used the \(N(H) = 1 \times 10^{19} \text{ cm}^{-2}\) contour of their model, where the ionized region of the Local Bubble abruptly ends, as the limit to the region from which the Sciama line could be detected. This contour is typically at 100 pc in the plane of the ecliptic. We have incorporated these results in equation (1), and we show the expected emission in the plane of the ecliptic for the Sciama scenario in Figure 2.

3. DISCUSSION AND CONCLUSIONS

The geocoronal oxygen background is obvious in the data shown in Figure 2, but in those view directions in which the absorption by the LIC is small because of the Sun's location within the cloud, the flux from radiatively decaying neutrinos should be far more intense than the oxygen emission. It is obvious by inspection that the emission predicted by the Sciama theory is not present.

We have fitted our data shown in Figure 2 to a model described by equation (1), in which we treat the background \(B\) and the photon production rate \(R_{\text{prod}}\) as parameters. Our best-fit value for \(B\) is 2200 photons s\(^{-1}\) cm\(^{-1}\) sr\(^{-1}\). Our best fit for \(R_{\text{prod}}\) is consistent with zero and has a 95% confidence upper limit of \(0.6 \times 10^{-16} \text{ s}^{-1} \text{ cm}^{-3}\), which is one-third of the production rate required by the theory.

The EURD data appear to be completely incompatible with the Sciama model of radiatively decaying massive neutrinos. We believe that the only parameters in this study that could be challenged, in principle, are the conversion factor from observed EURD counts to flux, and the LIC model. In evaluating the calibration issue, we note that while the most accurate conversion factor can be derived from stellar spectra, this result requires substantial justification (to be discussed elsewhere) and is not necessary for this work. The EURD in-flight calibration is firmly established to within a factor of 2 through our in-flight observations of the intensity of the geocoronal hydrogen Lyman lines. The counts-to-flux conversion using these in-flight results would have to be incorrect by more than a factor of 5 to reduce the predicted emission in the Sciama scenario to the level of the background shown in Figure 2 if all the uncertainties are added in the worst directions. We can think of no way that this could be realized. The other factor that could be challenged, the LIC model, would have to be incorrect by a factor of 20 to reduce the observed flux to the level of the background shown in Figure 2. This possibility is considered to be extremely unlikely (J. Linsky 1999, private communication).

Although we believe that our data rule out the Sciama model of radiatively decaying neutrinos, we note that we cannot exclude the earlier model of Melott with its longer lifetime. In this respect, it is intriguing to note that we do observe a faint line at \(~710 \text{ Å}\) in long integrations with the EURD instrument, which we have not been able to identify as either an upper atmospheric airglow line or as emission from the interstellar medium (Bowyer et al. 1999).

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REFERENCES

Athanassopoulos, C., et al. 1998a, Phys. Rev. Lett., 81, 1774
Athanassopoulos, C., et al. 1998b, Phys. Rev. B, 58, 2489
Bowyer, S., Edelstein, J., & Lampton, M. 1997, ApJ, 485, 52
Bowyer, S., Lampton, M., Peltoniemi, J., & Roos, M. 1995, Phys. Rev. D, 52, 3214
Bowyer, S., et al. 1999, in preparation
Chakrabarti, S., Paresce, F., Bowyer, S., & Kimble, R. 1983, J. Geophys. Res., 88, 4898

Davidsen, A., Kriss, G., Ferguson, H., Blair, W., Bowers, C., & Kimble, R. 1991, Nature, 351, 128
Fabian, A., Naylor, T., & Sciama, D. 1991, MNRAS, 249, 21
Feldman, P., et al. 1992, Geophys. Res. Lett., 19, 453
Flyn, B. C., Vallerga, J. V., Gladstone, G. R., & Edelstein, J. 1998, Geophys. Res. Lett., 25, 3253
Fukuda, Y., et al. 1998a, Phys. Lett. B, 433, 9
Fukuda, Y., et al. 1998b, Phys. Rev. Lett., 81, 1562
Gato, B., León, J., Pérez-Mercader, J., & Quirós, M. 1985, Nucl. Phys. B, 260, 203
López-Moreno, J. J., Morales, C., Gómez, J. F., Trapero, J., Bowyer, S., Edelstein, J., Lampton, M., & Korpela, E. 1998, Geophys. Res. Lett., 25, 2937
Melott, A. 1984, Soviet Astron., 28, 478
Melott, A., McKay, D., & Ralston, J. 1988, ApJ, 324, L43
Morales, C. 1999, ApJ, in press
Redfield, S., & Linsky, J. 1999, ApJ, in press
Rumph, T., Bowyer, S., & Vennes, S. 1994, AJ, 107, 2108

Sciama, D. 1990, ApJ, 364, 549
———. 1993, ApJ, 409, L25
———. 1995, ApJ, 448, 667
———. 1997a, ApJ, 488, 234
———. 1997b, MNRAS, 289, 945
———. 1998, A&A, 335, 12
Sciama, D., Persic, M., & Salucci, P. 1993, PASP, 105, 102
Sfeir, D., Lallement, R., Crifo, F., & Welsh, B. 1999, A&A, 346, 785
Welsh, B., Crifo, F., & Lallement, R. 1998, A&A, 333, 101