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(10) R. Stephen White
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DESCRIPTION OF RESEARCH AND RESULTS

A. Introduction

Much of the success of the UCR program in development of a neutron and gamma ray telescope and its use to search for solar neutrons and gamma rays is because of the support of the Office of Naval Research. The first double scatter neutron telescope was supported by the THEMIS program under the management of the Office of Naval Research. It was completed with the support of ONR #N00014-69-A-0200-5004. One flight was carried out in September 1971 and three during 1972. We are very grateful to ONR for this early support that enabled us to make the first measurements of atmospheric neutrons and set the lowest limits on neutrons from the quiet sun.

B. Double Scatter Neutron Telescope

The neutron double scatter telescope idea using scintillators was first suggested by White (1968). It involved two scatters of a neutron from two tanks of liquid scintillator separated by 1 m. The energy of a neutron and the source direction to a ring on the sky were obtained. The neutron energy and scattering angle were found from the proton recoil energy in the first scintillator and the time of flight of the neutron between the two scintillators. By using large area scintillators, 1 m × 0.5 m, thicknesses of 15 cm and separations between centers of 1 m, high sensitivities were obtained. Good angular resolution was obtained by dividing each of the tanks of liquid scintillator into cells 25 cm × 25 cm. Neutrons were separated from gamma rays by time of flight between the two scintillators.

Gamma rays take 3.3 ns to travel 1 m while neutrons of 100 MeV or less take more than 8 ns. Upward-moving neutrons and gamma rays were also separated from those moving downward by time of flight. The telescope had a large aperture for neutrons, 75° HWHM. This meant that neutrons from any angle up to 75° to the zenith could be measured simultaneously. The telescope was completed in late summer of 1971.

C. Telescope Flights

The first flight was carried out on September 26, 1971, from Palestine, Texas. The detector floated at 120,000 ft., 4.65 g/cm^2 residual atmosphere, and 20 hours of data were obtained. After minor modifications, a second flight was carried out from Palestine, Texas, on May 14, 1972. The balloon reached a float altitude of 4 g/cm^2 and had a flight duration of about 20 hours. The third flight was launched from Ft. Churchill in Hudson Bay, Canada, on July 22, 1972. This had a float altitude of 4 g/cm^2 and total data observation time of 19 hours. The final flight was carried out from Cape Girardeau, Missouri, on September 19, 1972. On this flight the balloon floated at 5 g/cm^2 for a period of 24 hours. At termination the parachute failed to open and the telescope underwent free fall to the earth landing in a pasture in Oklahoma. The detector was completely destroyed except for parts of the gondola which were salvaged and used on a later telescope.

This last flight was under sponsorship of ONR, flown by Ravens. ONR generously located year-end funds that paid a substantial amount toward the construction of a new double scatter telescope. The new telescope was completed and flown for the first time on May 13, 1975, from Palestine, Texas. It reached an altitude of 3 g/cm^2 and had a flight duration of 30 hours. In addition to measuring neutrons with this telescope, we also measured gamma rays by double Compton scattering. The new telescope was larger, 1 m × 1 m, and each scintillator tank was divided into 28 cells instead of the 8 cells of the first telescope. This enabled us to obtain better angular resolution. We also used mineral oil based scintillator with a high hydrogen to carbon ratio which gave us less background for observation of neutrons. With this telescope we have for the first time carried out measurements of gamma rays from 1 to 30 MeV. The second flight with this telescope was launched from Muskogee, Oklahoma, on May 23, 1976. This flight went to an altitude of 3 g/cm^2 and had a flight duration of 44 hours, the longest of any of our flights.

Our telescope is now in excellent working order. Several innovations have been added such as a small mini-computer for command, control and quick look data reduction and analyses. This telescope will be flown again this May from Palestine, Texas. We are now approaching the maximum of the solar cycle and thus, have a higher probability than in the past for seeing solar flares. We hope during this coming solar cycle to observe neutrons and gamma rays from solar flares.

D. Results

The observations of atmospheric and celestial gamma rays and search for solar neutrons and gamma rays have given important results that have been published in the appropriate scientific journals.

The properties of the neutron telescope were published by Grannan et al. (1972). The telescope is sensitive from 2 to 100 MeV. The detector was calibrated with 15 MeV neutrons at UCR and 50 MeV neutrons at UCD. The minimum detectable flux is 10^{-4} neutron/cm^2-s at a counting rate of one per minute, the energy resolution is 12% at 15 MeV and 30% at 100 MeV. The scattering angle of the incoming neutron can be measured to 10°.

The measurement of the earth's albedo neutrons from 10 to 100 MeV was published by Preszler et al. (1972). The albedo neutron energy distribution was nearly flat to 50 MeV and then decreased rapidly with energy. It was found that absolute energy distribution was of the correct strength and shape for the albedo neutrons to be the source of the protons trapped in Earth's inner radiation belt.

In a review of the high energy proton radiation belt, White (1973) described the experiments and theories to explain the high energy protons trapped in the earth's radiation belt. The theory of cosmic ray albedo neutron decay injection of protons, including radial diffusion and change in the earth's dipole moment, were considered along with losses of protons by ionization and nuclear collisions. It was found that the measured albedo neutron escape current was sufficient to supply the radiation belt trapped protons above 30 MeV.

In a study of the equatorial inner belt protons from 2 to 200 MeV Claflin and White (1974) found that the diffusion theory could account for the observed flux of low energy protons provided that the diffusion coefficient increases at smaller values of the first invariant. The effects of Coulomb energy loss, nuclear inelastic scattering, and the secular decrease of the earth's magnetic field were included.

In the paper "A Burst of Energetic Gamma Rays" (Koga, Simnett and White, 1974) a burst of gamma rays with energies greater than 1 MeV was reported that occurred on May 14, 1972. The burst had a rise time of 6±3 sec, a time duration of 2 min and a decay time of one min. This event was similar to three events previously found from balloons by other investigators. One possible explanation for the gamma ray burst is that it is of solar origin. The onsets of two subflares occurred one minute after the rise in the observed gamma burst and their maxima occurred 2 and 4 min later. The chance occurrence in the 3 min interval of the gamma ray burst is 0.01 so that a chance coincidence between the gamma ray burst and the Hα flare plus x-ray peak cannot be ruled out. The more likely explanation appears to be that this burst originated in the sun.

The angular distribution and altitude dependence of atmospheric neutrons from 10 to 100 MeV (Preszler, Simnett and White, 1974) were reported. The ascent and float measurements were made on a launch from Palestine, Texas, on September 26, 1971. The intensity of both the downward- and the upward-moving neutrons is maximum at 100 g/cm^2 of residual atmosphere. Neutron angular distributions were reported from 20° to 80° and 100° to 160° for 10 to 100 MeV neutrons. The omnidirectional fluxes at altitudes of 5, 50, 100 and 200 g/cm^2 of residual atmosphere were in good agreement with recent theoretical calculations of Armstrong et al.

Simnett (1973) reviewed the relativistic electron events observed in interplanetary space. The relationships between solar X-ray and radio emissions and relativistic electrons were examined and the relevance of the observations to solar flare acceleration models were discussed. A model was outlined that can account for the release of electrons from the sun in a manner consistent with observations of energetic solar particles and electromagnetic solar radiation.

Predictions of Jupiter's electron and proton radiation belt fluxes based mainly on decimeter observations in 1966 and 1968 were made by Stansberry and White (1973). Extensive calculations modeling radial diffusion of particles inward from the solar wind and electron synchrotron radiation were used to relate the predictions and observations.

Detailed calculations were carried out (Stansberry and White, 1974) of the fluxes of the electrons and protons in Jupiter's radiation belts. The source was radial diffusion inward from the solar wind and losses occurred by synchroton radiation. Good agreement was obtained with the observed electron fluxes but the calculated flux of protons was larger than the observed number by a factor of about 100.

A new large double scatter telescope for gamma rays and neutrons was described by Herzo et al. (1975). This telescope has a 1 m^2 area sensitive to gamma rays from 0.5 to 30 MeV and to neutrons from 2 to 100 MeV. Gamma rays are identified by Compton scatters in each of two large liquid scintillator tanks each divided into 28 cells and each viewed by a separate photomultiplier. The neutrons are separated from the gamma rays by time of flight. The efficiency for gamma rays is 3% at 4 MeV, 1% at 0.5 MeV and 0.4% at 30 MeV. For a neutron point source, the peak efficiency is 8% at 6 MeV and falls to 1% at 3 MeV and to 0.4% at 100 MeV. The cone angle resolutions are about 10° HWHM.

The telescope was also described by Zych et al. (1975). The energy resolution was found to be 24% HWHM for a 10° scattering angle, decreasing to 5% at a scattering angle of 60° for a 6.1 MeV gamma ray incident. The timing resolution for sea level muons was found to be 1.5 ns FWHM.

A cosmic gamma ray burst was observed on May 14, 1975, by Herzo et al. (1976). The initial rise time to 90% of maximum was 0.01 sec and the time duration of the burst was 0.1 sec. Time structure was observed down to 5 ms resolution of the telescope. The direction of the source, with 90%

confidence, was limited to a circle with radius of 25° and center at a R.A. of 248° and a declination of +22°. Two additional burst candidates of 6.4 and 6.5 σ were found.

The upper limits to the quiet-time solar neutron flux from 10 to 100 MeV was published by Moon et al. (1976). No solar flares occurred during the flights. Upper limits to the quiet-time solar neutron fluxes at the 95% confidence level are 2.8, 4.6, 9.6 and 9.0 × 10^{-4} neutrons/ $cm^{-2}s^{-1}$ in the energy intervals of 10-30, 30-50, 50-100 and 10-100 MeV.

Additional information on atmospheric neutrons were published by Preszler et al. (1976). These were based on additional calibrations of the UCR double scatter neutron detector carried out at UC Davis. Theoretical angular distributions are in general agreement with the experimental peaks for vertical upward and downward moving neutrons. The theoretical neutron escape values were in agreement with experimental values from 10-100 MeV. Our experimental fluxes agree with those of Kanbach et al. in the overlap region from 70 to 100 MeV.

Atmospheric gamma ray angle and energy distributions from 2 to 25 MeV were reported by Ryan et al. (1977a,b). The distributions were obtained from the UCR double Compton scatter gamma ray telescope flown on a balloon from Palestine, Texas, to 3.0 g/cm^2 residual atmosphere. Growth curves from 3.4 to 100 g/cm^2 were used to determine the downward moving atmospheric fluxes. Results are given for six energy intervals from 2 to 25 MeV and for five angle intervals from 0° to 50°. The absolute fluxes of upward moving gamma rays from 130° to 170° at 4.2 g/cm^2 are 12±1 and 9±2 for 3 to 10 and 10 to 25 MeV.

The cosmic diffuse gamma rays at medium energies were reported by White et al. (1977) in six energy intervals from 2 to 25 MeV. The observed fluxes are compatible with the energy distribution of $2.65 \times 10^{-2} E^{-2.08}$ (photons/cm^2-s-ster-MeV) proposed by Dennis et al. at lower energies, steepened at higher energies to meet the slope of $E^{-2.4}$ of Fichtel et al. for energies above 35 MeV. No statistically significant deviation from isotropy in direction of the cosmic diffuse gamma rays were observed. Upper limits were given of a few $\times 10^{-3}$ photons/cm^2-s for a number of possible sources.

Gamma rays of 3 to 25 MeV from the galactic anti-center and pulsar NP 0532 were reported by Wilson et al. (1977). Gamma rays from the galactic anticenter were observed as the Crab Nebula passed overhead within 10° of the zenith. Pulsed gamma rays from NP 0532 were observed at a 4.4 σ significance level. Our total flux from 3 to 25 MeV is $4.9 \pm 2.0 \times 10^{-3}$ photons/cm^2-sec. The pulsed flux from NP 0532 from 3 to 25 MeV is $4.3 \pm 2.6 \times 10^{-4}$ photons/cm^{-2}s^{-1}. The ratio of the total to the pulsed flux from 3 to 25 MeV is 11 ± 8.

An improved response with a double scattering medium energy gamma ray telescope was described by Zych et al. (1977). The telescope would utilize the double scattering technique combining both plastic and NaI(Tℓ) scintillation detector arrays with time of flight. NaI(Tℓ) in the second arrays gave much improved energy and angular resolutions and improved efficiencies. The first array consists of a group of long plastic scintillators were the lateral position is determined by the difference in scintillation light arrival times at the two ends.

Cosmic diffuse gamma rays from 2 to 25 MeV were reported by White et al. (1977). The flux of cosmic diffuse gamma rays with energies from 2 to 3, 3 to 5, 5 to 7 and 7.5 to 10 MeV were reported and upper limits were given for energies of 10 to 15 and 15 to 25 MeV. These measurements were obtained with the UCR double Compton scatter gamma ray telescope flown on a balloon launched on May 13, 1975, from Palestine, Texas. No statistically significant deviation from isotropy in direction of the cosmic diffuse gamma rays were observed. These observations gave upper limits of a few times 10^{-3} photons/cm^{-2}s^{-1} for a number of possible sources.

Evidence that cosmic gamma ray bursts are galactic are presented by White et al. (1978). Observations from the Muskogee, Oklahoma, May 23, 1976, flight were combined with our previous results from the May 13, 1975, flight from Palestine, Texas, and the observations of Bewick et al. and of Nishimura et al. to give strong evidence that cosmic gamma ray bursts are galactic. It appears that the recently discovered x-ray bursts and gamma ray bursts have a common origin.

The publications of our research during the time of the ONR support are listed in Appendix A.

E. Participants in the Scientific Program

A number of post docs, graduate students and undergraduate students participated in our neutron and gamma ray program during the time of the ONR support and are listed in Appendix B. The theses completed during the ONR support are given in Appendix C.

APPENDIX A

List of Publications

R. T. Grannan, R. Koga, W. A. Millard, A. M. Preszler, G. M. Simnett and R. S. White, "A Large Area Detector for Neutrons Between 2 and 100 MeV," Nuclear Instruments and Methods 103, 99-108 (1972).

A. M. Preszler, G. M. Simnett and R. S. White, "Earth Albedo Neutrons From 10 to 100 MeV," Physical Review Letters 28, 982-985 (1972).

S. Moon, G. M. Simnett and R. S. White, "A Search for Solar Neutrons From 10-100 MeV," Proceedings of the 13th International Cosmic Ray Conference, Denver, Colorado, USA, 1583-1588 (1973).

R. S. White, S. Moon, A. M. Preszler and G. M. Simnett, "Earth Albedo and Solar Neutrons," Space Research 13, 683-687 (1973).

R. Stephen White, "High-Energy Proton Radiation Belt," Reviews of Geophysics and Space Physics 11, 595-632 (1973).

E. S. Claflin and R. S. White, "A Study of Equatorial Inner Belt Protons From 2 to 200 MeV," Journal of Geophysical Research 79, 959-965 (1974).

R. Koga, G. M. Simnett and R. S. White, "A Burst of Energetic Gamma-Rays," Proceedings of Ninth ESLAB Symposium, June 10-12, 1974, Frascati, Italy. Edited by B. G. Taylor, ESRO SP-106, 31-36 (1974).

A. M. Preszler, G. M. Simnett and R. S. White, "Angular Distribution and Altitude Dependence of Atmospheric Neutrons From 10 to 100 MeV," Journal of Geophysical Research 79, 17-22 (1974).

G. M. Simnett, "Relativistic Electron Events in Interplanetary Space," Space Science Reviews 16, 257-323 (1974).

K. G. Stansberry and R. S. White, "Jupiter's Radiation Belts," Journal of Geophysical Research 79, 2331-2342 (1974).

D. Herzo, R. Koga, W. A. Millard, S. Moon, J. Ryan, R. Wilson, A. D. Zych and R. S. White, "A Large Double Scatter Telescope for Gamma Rays and Neutrons," Nuclear Instruments and Methods 123, 583-597 (1975).

A. D. Zych, D. Herzo, R. Koga, W. A. Millard, S. Moon, J. Ryan, R. Wilson, R. S. White and B. Dayton, "Large Area Double Scattering Telescope for Balloon-Borne Studies of Neutrons and Gamma Rays," IEEE Transactions on Nuclear Science NS-22, 605-610 (1975).

D. Herzo, B. Dayton, A. D. Zych and R. S. White, "A Cosmic Gamma-Ray Burst on 1975 May 14," The Astrophysical Journal 203, L115-L118 (1976).

S. Moon, G. M. Simnett and R. S. White, "Upper Limits to the Quiet-Time Solar Neutron Flux From 10 to 100 MeV," The Astrophysical Journal 207, 630-638 (1976).

A. M. Preszler, S. Moon and R. S. White, "Atmospheric Neutrons," Journal of Geophysical Research 81, 4715-4722 (1976).

J. M. Ryan, S. H. Moon, R. B. Wilson, A. D. Zych, R. S. White and B. Dayton, "Atmospheric Gamma-ray Angle and Energy Distributions From 2 to 25 MeV," Proceedings of the 15th International Cosmic Ray Conference, Plovdiv, Bulgaria, 1, 73-78 (1977).

J. M. Ryan, B. Dayton, S. H. Moon, R. B. Wilson, A. D. Zych and R. S. White, "Atmospheric Gamma Ray Angle and Energy Distributions From 2 to 25 MeV," Journal of Geophysical Research 82, 3593-3601 (1977).

R. S. White, S. H. Moon, J. M. Ryan, R. B. Wilson, A. D. Zych and B. Dayton, "Cosmic Diffuse Gamma-Rays at Medium Energies," Proceedings of the 15th International Cosmic Ray Conference, Plovdiv, Bulgaria, 1, 100-105 (1977).

R. B. Wilson, S. H. Moon, J. M. Ryan, A. D. Zych, R. S. White and B. Dayton, "Gamma-Rays of 3 to 25 MeV from the Galactic Anti-Center and Pulsar NP 0532," Proceedings of the 15th International Cosmic Ray Conference, Plovdiv, Bulgaria, 1, 24-29 (1977).

A. D. Zych, R. B. Wilson, E. Zanrosso, R. S. White and B. Dayton, "Improved Response with a Double Scattering Medium Energy Gamma Ray Telescope," Proceedings of the 15th International Cosmic Ray Conference, Plovdiv, Bulgaria, 9, 6-10 (1977).

R. S. White, B. Dayton, S. H. Moon, J. M. Ryan, R. B. Wilson and A. D. Zych, "Cosmic Diffuse Gamma Rays From 2 to 25 MeV," The Astrophysical Journal 218, 920-927 (1977).

R. S. White, J. M. Ryan, R. B. Wilson, A. D. Zych and W. B. Dayton, "Evidence that Cosmic Ray Bursts are Galactic," accepted for publication in Nature (1978).

APPENDIX B

Scientific Collaborators

Principal Investigator:	R. Stephen White
Co-Investigators:	Allen D. Zych W. Bruce Dayton
Post Docs:	Dennis Herzo Rokutaro Koga Shin Moon Alan Preszler
Graduate Students:	Thomas G. Burnett E. Scott Claflin Richard Gibbons Ralph Grannan Dale Keim Rokutaro Koga Lee Mickelson Shin Moon Alan Preszler James Ryan Starnes Walker Robert Wilson Eddie Zanrosso
Undergraduate Students:	Ron Bardarson Dennis Gilliam David Page Tom Wissler Steven Wsol

APPENDIX C

Theses Completed

Edward Scott Claflin III - December 1971
"Identification of Solar Neutron Events by Observation of Radiation Belt Proton Fluxes"

Lee Mickelson - June 1972
"Study of the Spatial Distributions of Off-Equatorial Protons at L = 1.4-1.3"

Kent Gardner Stansberry - December 1972
"Radiation Belt Diffusion Applied to Jupiter"

Alan Melvin Preszler - March 1973
"Earth Albedo Neutrons From 10 to 100 MeV"

Starnes Elbert Walker - December 1973
"Time Correlation of Heavy Cosmic Ray Nuclei"

Rokutaro Koga - June 1974
"Cosmic and Atmospheric Gamma-Rays From 3 to 15 MeV"

Shin Haeng Moon - April 1976
"A Search for Solar Neutrons From 10 to 100 MeV"

Theses to be completed:

Robert Wilson and James Ryan to be completed in June 1978.