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Positron–Electron Pairs in Astrophysics

(Goddard Space Flight Center, 1983)

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PREFACE

A workshop on Positron-Electron Pairs in Astrophysics was held at the Goddard Space Flight Center in January 1983. This workshop brought together observers and theorists actively engaged in the study of astrophysical sites, as well as the physical processes therein, where positron-electron pairs have a profound influence on both the overall dynamics of the source region and on the properties of the emitted radiation. This was the first meeting of its kind to be devoted exclusively to positron-electron pairs in astrophysical sources. We hope that the present volume, which constitutes the workshop proceedings, will be a valuable reference on the subject.

The most obvious signature of positron-electron pairs is their annihilation radiation, generally observed as a line at 0.511 MeV. This line has been seen from the Galactic Center, where observations performed with detectors flown on balloons and on the Third High Energy Astronomical Observatory (HEAO-3) have revealed a very narrow, very intense and time variable line at precisely 0.511 MeV. These observations were summarized at the workshop, together with the theories that were suggested to account for this unusual source at the nucleus of our galaxy. It has been proposed that the energy source for the positrons responsible for the observed radiation is a massive black hole. The positrons are produced either by multibillion degree photon distributions or in nonthermal processes associated with a beam of high energy photons and particles accelerated by induced electric fields. Other proposed possibilities were a recent supernova or a pulsar along the line of sight to the Galactic Center.

Positron-electron annihilation radiation is observed also at energies other than 0.511 MeV. The best known example is the emission line at about 0.4 MeV observed from gamma-ray bursts by detectors on the Venera and ISEE-3 spacecraft. The shift from energies greater than 0.5 MeV is generally believed to be due to the gravitational redshift at surfaces of neutron stars, and this result provides strong evidence that gamma-ray bursts originate from these objects.

Exciting new observations of gamma-ray bursts were the recurrent events from the source direction of the March 5, 1979 burst presented by E. P. Mazets. This last-minute contribution has not been submitted for publication in the present volume. Other interesting gamma-ray burst observations concern the optical identification of bursts and high time resolution measurements of burst spectra, which indicate variations of the spectral shape during the course of a single event. A confirmation of cyclotron line observations, using data from HEAO-1, was also presented.

Even though annihilation radiation has not yet been directly observed from pulsars, the role of positron-electron pairs in pulsar magnetospheres has long been recognized. In particular, the radio and gamma-ray emission is generally believed to be closely associated with an electromagnetic cascade. These cascades are thought to produce the large pair densities in the magnetosphere necessary, in most models, for the observed coherent radio emission.

Among new observational results on pulsars presented at the workshop was the recent discovery, at Arecibo, of a millisecond pulsar. This object, because of its very low magnetic field, may be able to test our current ideas about the relation of positron-electron pairs to pulsar radio emission.

Another class of astrophysical sites where positron-electron pairs may play an important role are active galaxies. Even though the annihilation line has not yet been seen from such objects, the large observed photon luminosities above pair production threshold and the compact sizes of these objects lead to strong expectations for positive detections of annihilation radiation from active galaxies. Some proposed sites of high energy radiation and subsequent positron-electron production in active galaxies are electromagnetic cascades in relativistic jets, accretion shocks around black holes and hot accretion disks.

The large number of papers on physical processes involving positron-electron pairs indicates that this is currently a very active field of research. It also suggests that the understanding of the role of positron-electron pairs in astrophysical sources requires a deeper study of the basic processes. Results were presented on equilibria in relativistic pair plasmas, both with and without magnetic fields, pair production and annihilation in superstrong magnetic fields, and stimulated annihilation processes.

Two papers on gamma-ray lines from solar flares were also presented. These lines were observed by an instrument that is currently flying on the Solar Maximum Mission. Although positrons do not play an important dynamical role in flares, the Sun, because of its proximity, is the only site from which a full spectrum of gamma-ray lines has so far been seen. As such, solar flares can be used to test mechanisms of gamma-ray production and particle acceleration, both of which are important for the compact astrophysical sites that constituted the main topic of the workshop.

In summary, we believe that an important new astrophysical research topic is opening up at the present time, one that involves relativistic and highly magnetized plasmas with large concentrations of positron-electron pairs. As attested by the papers presented in this volume, a growing body of observations provides evidence for the existence of such plasmas and a considerable amount of theoretical work reveals the exciting new physics that govern them. We hope that this volume will serve as a useful summary of these observations and theories.

The success of the workshop depended on many individuals. In addition to ourselves, the scientific organizing committee consisted of Jonathan Arons, University of California at Berkeley, Marvin Leventhal, Bell Laboratories, Alan P. Lightman, Harvard-Smithsonian Center for Astrophysics and Richard E. Lingenfelter, University of California at San Diego. W.A. Hilley provided outstanding secretarial help prior to and during the workshop and M.E. Schronce provided valuable assistance in the preparation of this volume. We especially thank J.M. McKinley for his help in editing the papers. We are also indebted to the various support elements of the Goddard Space Flight Center for providing transportation, projection equipment and meeting rooms. Financial support for the publication of this volume was provided by NASA.

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WELCOMING REMARKS

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It is a pleasure for me to welcome you here today to the Goddard Space Flight Center for what promise to be 3 busy and exciting days devoted to electron positron pairs in astrophysics.

It is particularly appropriate for this workshop to be taking place at this time just after the 50th anniversary of the discovery of the positron and the 10th anniversary of the detection of annihilation radiation from the Sun.

The positron was discovered just over 50 years ago on August 2, 1932, by Carl Anderson, a young post-doctoral research fellow at Cal Tech, using a Wilson Cloud Chamber in a strong magnetic field. The existence of the positron had been predicted by Paul Andre Maurice Dirac in his relativistic solutions to the Schroedinger Equation, although he originally thought that the unfilled holes in the distribution of negative energy electrons would be protons. The existence of the annihilation radiation that occurs when a positron and electron come together was implied in Dirac's theory. It was first explicitly stated by Blackett and Occhialini in a paper published in the proceedings of the Royal Society on February 7, 1933, in which they said,

> ". . . it is necessary to come to the same remarkable conclusion that has already been drawn by Anderson from similar photographs. This is that some of the tracks must be due to particles with a positive charge but whose mass is much less than that of a proton."
>
> "The existence of positive electrons in these showers raises immediately the question of why they have hitherto eluded observation. It is clear that they can have only a limited life as free particles since they do not appear to be associated with matter under normal conditions. It is conceivable that they can enter into combination with other elementary particles to form stable nuclei and so cease to be free, but it seems more likely that they disappear by reacting with a negative electron to form two more quanta. This latter mechanism is given immediately by Dirac's theory of electrons."

Later on June 9, 1933, in a paper in the Physical Review, Oppenheimer and Plesset wrote,

> "This is what we should expect from the pairs, which should lose practically all of their kinetic energy in

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> passing through matter, and in which the anti-electron near the end of its range should combine with an electron with the radiation of two quanta of about a half-million volts."

That of course was all 50 years ago. Ten years ago, almost precisely on the 40th anniversary of Anderson's discovery, Ed Chupp and his colleagues from the University of New Hampshire first saw the solar 511-keV line from the August 4, 1972 solar flare in their OSO-7 gamma-ray detector. Later Jack Trombka saw annihilation radiation from the moon on Apollo flights. Marvin Leventhal observed it from the galactic center from a balloon and Professor E. P. Mazets from Leningrad first saw annihilation radiation from a gamma-ray burst. All of these people are here today, in fact practically everyone who has ever seen positron electron annihilation radiation of astrophysical origin is here. What you are finding out about the Universe with this tool is just as interesting as the original studies which led to the discovery of the positron. You have a large and enthusiastic group concerned with an exciting subject. We're very pleased you are here. I know you will have a good time. Welcome to Goddard.

SOLAR γ-RAY LINES

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ABSTRACT

The Gamma Ray Spectrometer on the Solar Maximum Mission (SMM) satellite has observed emissions produced by nuclear reactions in over 20 separate solar flares. The observed intensity from different flares of some of these emissions ranges over a factor of 100 and the time scale for their production ranges from 10 s pulses, to complete events lasting over 1000 s. The emissions include narrow and broadened prompt γ-ray lines from numerous isotopes from ^{7}Li to ^{56}Fe and cover the energy range 0.431 MeV (^{7}Be) to 7.12 MeV (^{16}O). The instrument has also observed emissions at energies greater than 10 MeV from the decay of π^0 mesons, from electron bremsstrahlung, and from the direct observation of $> 10^2$ MeV solar neutrons. The intensity, temporal and spectral properties of these emissions will be reviewed from the point of view that solar flares represent an astrophysical particle acceleration site.

INTRODUCTION

The discovery of cosmic rays in 1908 marks the beginning of the general field of high energy astrophysics[1]. This discovery immediately led to questions concerning the location and the mechanism responsible for the production of these energetic particles. These questions are still unresolved and studies of cosmic rays have shed little light on the process, other than to show that the process must still be going on today.

Recently, the location of a nearby acceleration process was identified with the discovery of solar cosmic rays associated with solar flares[2,3]. Again, studies of solar cosmic rays have not led directly to a full understanding of either the exact location or the mechanism of the acceleration process, beyond reconfirmation of its close association with the multifaceted phenomenon known as a solar flare. Lingenfelter and Ramaty[4] pointed out that another way of investigating any acceleration process was to study the properties of the energetic X-rays, γ-rays, and neutrons which must always be produced as the accelerated particles interact with matter in and near the acceleration region.

The first successful observations of nuclear γ-rays from solar flares were made in August 1972[5]. These observations have been extensively studied and have led to a model with two separate steps of acceleration or heating[6,7]. The first step is relatively impulsive in time and produces energetic electrons up to > 100 keV. The second step follows the first by minutes and produces a

*Presented in behalf of the SMM Gamma Ray Astronomy Team.

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nonthermal spectrum of energetic nucleons and relativistic electrons. It is thought that some of the particles from this second process stay in the solar atmosphere to produce the observed nuclear γ-ray emission and some escape from the Sun to be observed near 1 AU as solar cosmic rays.

One of the advantages of this model is that the time-scale of the second acceleration process is consistent with a Fermi-type process, a process which has been considered for the acceleration of cosmic rays in other astrophysical sources. Hence, the theoretical pictures were complementary and it was felt that the acceleration process in solar flares, if not completely understood, at least was on firm theoretical ground[8].

In this review I will summarize some of the observations made with the Gamma Ray Spectrometer (GRS) on the SMM spacecraft, which was launched on 1980 February 14. For the most part, the results presented in this review come from analyses of all of the 70 flares observed at energies > 300 keV during the first 2 years of operation. These results include electron bremsstrahlung X-rays and prompt γ-ray lines from excited nuclei produced in a variety of nuclear reactions. They also include secondary γ-ray lines from the annihilation of positrons, the capture of neutrons, and the first observation of solar neutrons. I will use these results to discuss the temporal evolution of the acceleration process; the range of observed photon yields from this sample of 70 flares; and in one flare I will set limits on the time-constant of the spectral shape evolution of the accelerated particles. Finally, I will discuss the current status of our efforts to determine the relative isotopic abundance in both the accelerated particles and the target region.

TEMPORAL EVOLUTION

During a solar flare observation the (4.1-6.4) MeV energy band in the GRS is dominated by prompt ($< 10^{-12}$ s), broad and narrow nuclear line emissions from carbon, nitrogen, and oxygen (CNO)[10]. The spectral and temporal properties of these nuclear emissions have been shown to be most consistent with ions interacting in a high density target[11]. Because of the rapid rate of particle energy loss in the high density target, it is believed that these emission time-profiles also closely represent the yield of energetic ions from the acceleration process.

Fig. 1 shows the counting rate time-profile in this energy band for 2 flares which represent extremes in temporal profiles among the 70 flares observed by GRS. The flare on 1980 June 21 is one of the "fastest" and the flare on 1981 April 27 is one of the "slowest". As can be seen, the majority of the emission in both flares is made up of semi-symmetric pulses or injections of accelerated particles. A characteristic time for these pulses is $\sim$10 s (FWHM) for the fast flare and $\sim$200 s (FWHM) for the slower one. A study of the slow 1981 April 27 flare, at higher time resolution, shows that its emission is not made up of a large