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**INTERNATIONAL GAMMA RAY SYMPOSIUM
"THE STRUCTURE AND CONTENT OF THE
GALAXY AND GALACTIC GAMMA RAYS"**

A REVIEW

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International Gamma Ray Symposium

"THE STRUCTURE AND CONTENT OF THE GALAXY AND GALACTIC GAMMA RAYS"

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International Gamma Ray Symposium

"THE STRUCTURE AND CONTENT OF THE GALAXY AND GALACTIC GAMMA RAYS"

A Review

An International Gamma Ray Symposium entitled "THE STRUCTURE AND CONTENT OF THE GALAXY AND GALACTIC GAMMA RAYS" was held at NASA-Goddard Space Flight Center, Greenbelt, Maryland, June 2-4, 1976. This review is prepared from notes taken during the symposium and from manuscripts presented for the proceedings. The proceedings (1976) are available in preprint form from members of the organizing committee and will be published in book form by NASA. A list of the organizing committee members and the symposium speakers is included with the reference to the proceedings.

Compared with its predecessor held at Goddard in 1973 (Stecker and Trombka 1973), this symposium comprised the presentation of a wider variety of observational results, broadening the range of information considered while focussing astrophysical interest on the galaxy. Radio and γ -ray data were combined to paint detailed maps describing the content and distribution of matter in the galaxy and to define limits on the origin and confinement of cosmic rays.

Presented in the invited papers were the most recent results from 1) observations of diffuse galactic γ rays and discrete γ -ray sources from SAS 2 and from COS B, the European's γ -ray satellite launched less than one year ago; 2) infrared and radio observations of the galaxy and extragalactic radio surveys; 3) ground-based observations of high-energy γ rays from discrete sources; 4) interpretations of these measurements in terms of galactic structure, pulsar theory, and cosmic rays; and

5) the experimental and theoretical outlook for γ -ray lines and low-energy γ -ray astronomy. Contributed papers were incorporated in "Hot Topics" sessions. A panel discussion on the last day of the symposium provided a forum for summary statements of the most pressing questions and suggestions on how answers might best be obtained. Highlights from the presentations on galactic structure, discrete sources, and low-energy γ rays are described in Sections 2, 3, and 4 respectively. In Section 5, this review concludes with a summary of the new data and their interpretations.

GALACTIC STRUCTURE

The relationship of γ -ray observations to an understanding of galactic structure provides the most dramatic example of the growing role of γ -ray astronomy in the field of astrophysics. At the Gamma-Ray Symposium held at Goddard in 1973, the only results presented on electromagnetic radiations from the galaxy at energies between 35 and several hundred MeV were the tantalizing preliminary results from SAS 2 which had been launched less than six months earlier. The data confirmed the previous OSO 3 observations that a high intensity of γ rays come from the galactic disc, particularly the inner galaxy; but more details awaited further observations and analysis.

The success achieved with SAS 2 is evident in the results presented at this symposium. D. J. Thompson reviewed the galactic distribution of γ -ray emission as observed with SAS 2 and showed that the features evident in this γ -ray map are correlated with other measures of the matter, magnetic field, and cosmic-ray distributions in the galaxy. The two-component latitude distribution, observed in the region of the galactic center, was confirmed with the COS B data presented by J. A. Paul. These data suggest that the emission arises from two sources, one nearby at a distance ≤ 1 kpc and another more distant at > 3 kpc.

Interest in galactic γ -ray emission is stimulated primarily because γ -rays are probes of the energetic interactions in which they are produced and because they are able to penetrate the interstellar medium relatively undisturbed by propagation effects. Interpretation of the γ -ray observations in terms of galactic models requires simultaneous consideration of

observations of the galaxy at other wavelengths. Studies reported by N. Z. Scoville and W. B. Burton show a concentration of molecular clouds in the galactic nucleus and between galactic radii of 4 to 8 kpc. This region of increased molecular hydrogen density corresponds to the region of enhanced 100-MeV γ -ray emissivity, supporting the suggestion by F. W. Stecker that γ rays are produced primarily through cosmic ray interactions in clouds of molecular hydrogen. Both ionized hydrogen and molecular hydrogen show pronounced small-scale structure in contrast with atomic hydrogen which is relatively uniform in distribution. Results on the molecular and atomic hydrogen densities within a region of 1 kpc of the sun were reported by E. B. Jenkins from observations of UV spectra with the Copernicus satellite. The ratio of molecular to atomic hydrogen was found to vary markedly, yielding results that are consistent with the observations reported by Burton but uncertain to within a factor of 2. The status of infrared measurements and the information to be obtained from such observations were discussed by G. G. Fazio and J. L. Puget. Fazio pointed out that observed IR emission might be proportional to the amount of dust along the line of sight. Puget noted, however, that if the primary energy sources are within a cloud and if there is enough dust in the cloud to thermalize, the IR emission is independent of the amount of dust and depends rather on the temperature of the cloud. In this case the IR emission would provide an independent probe of the energy radiated by a dust cloud while γ -ray and radio observations provide measures of densities in regions which are optically thin for these radiations.

The distribution of pulsars in the galaxy was reported by J. H. Seiradakis to be correlated with that of other young galactic objects, but in a layer thinner than the distribution of cosmic ray electrons. From studies of nonthermal radio emission, J. E. Baldwin concluded that the emissivity extends to heights of several kpc above the galactic plane. If this is synchrotron radiation from interactions of cosmic ray electrons in galactic fields, as is generally assumed, then electrons are much more widely distributed than other matter in the galaxy.

Interpretations of all these complementary observations were discussed from a variety of perspectives. W. W. Roberts, Jr. suggested that large-scale galactic shock waves in the interstellar gas may play an important role in star formation, molecular formation, and the development of spiral structure. This density-wave model provides an explanation for the separation of molecular and neutral hydrogen and could account as well for the very structured distributions of molecular and ionized hydrogen, supernova remnants, and pulsars. The subject of cosmic ray propagation and their galactic containment was reviewed by E. N. Parker, who outlined both the implications and the problems presented by current observations. Cosmic rays with energies less than 10^{16} eV/nucleon are trapped by the galactic magnetic fields and can escape only when their lines of force escape. Depending on the lifetime of cosmic rays in the galaxy, which is estimated to be as low as 10^6 yr and as great as 10^8 yr, the energy input to the galaxy in cosmic rays may be the dominant energy source or it may be negligible. Parker suggested that under certain assumptions supernova remnants might be inadequate to explain the largest energy

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input, 5×10^{-26} erg/cm³-sec, should the shortest lifetime prove to be correct. However, the γ -ray observations together with the radio measurements of matter distribution in the galaxy are readily explained by a supernova origin of cosmic rays. This apparent conflict could be solved by adopting the longer lifetime which is consistent with the recent Be¹⁰ measurements and with the cosmic ray confinement model described by B. Peters, but which leads to another question, namely how to explain the lack of a break in the observed cosmic-ray electron spectrum.

The role that gamma-ray observations can play in describing large-scale galactic structure was reviewed and summarized by D. A. Kniffen and F. W. Stecker. Kniffen noted that cosmic ray electrons and protons can be studied independently from different energy ranges of the γ -ray spectrum. The γ -ray distribution is best described by a structured confinement of cosmic rays, but definitive results on spiral structure require more accurate measurements, especially of the galactic distribution of matter. F. W. Stecker discussed the production processes for γ rays and their significance for inner and outer regions of the galaxy. He demonstrated the strong correlation between the cosmic ray distribution, deduced from γ -ray and complementary measurements, and the supernova remnant and pulsar distributions. These observations favor the theory of galactic origin for cosmic rays, incorporated in the model suggested by Stecker. This model is not, however, consistent with confinement of the cosmic rays in spiral arms.

DISCRETE SOURCES

In addition to maps of the diffuse γ -ray sky, the SAS-2 telescope has enabled identification of six discrete γ -ray sources. Of these six sources, four are pulsars: the Crab Pulsar NP0531 + 21, the Vela Pulsar PSR0833-45, and two radio pulsars PSR 1818-04 and PSR 1747-46. By contrast, only the Crab Pulsar was presented as a γ -ray source at the symposium in 1973. R. C. Hartman reported that the SAS-2 data were searched for all known radio pulsars lying in regions of the sky scanned with SAS-2 and having sufficiently well known timing properties to provide adequate phase information during the observations. In all, 75 pulsars were studied for γ -ray pulsations with the observed radio periods. From the results of this search, several general conclusions were reported. Only the youngest γ -ray and radio pulsar, the Crab, is observed at optical and x-ray wavelengths. The two most recently identified sources, PSR 1818-04 and PSR 1747-46 are older and put most of their energy into γ -rays. Pulsars observed at γ -ray energies have apparent ages less than 10^6 years and are estimated to contribute approximately 5% of the observed galactic γ -ray luminosity.

Recent COS-B observations confirm the flux levels and pulsed characteristics of the Crab γ -ray emission determined from SAS-2 observations, but yield pulsed flux levels from Vela approximately twice those determined with SAS-2. The apparent difference in the Vela observations may be explained as temporal variability, but as such is very difficult to interpret theoretically. In presenting the results of COS-B pulsar observations, R. Buccheri noted the remarkable similarity between the pulse structure in the Crab and Vela γ -ray light curves and the contrast

in the optical and X-ray regions of the spectrum. From the Crab, x-ray and optical pulsations are observed in phase with the radio and γ -ray pulsations; while from Vela, which is the strongest γ -ray source, no x-ray or optical pulsations are observed. In his presentation of a pulsar model, H. Ogelman further noted that γ rays carry more than 5 orders of magnitude more energy than the radio emission from pulsars. Both the apparent consistency of the γ -ray light curves and the large energy flux in γ rays suggest that pulsed γ -ray emission may be the most direct manifestation of the fundamental process characterizing pulsars.

An ingenious instrumental technique for obtaining accurate pulsar-phase information was employed in the COS-B system. An x-ray detector, sensitive in the energy range 2-12 keV, was employed as a Pulsar Synchronizer for sources with periodic x-ray emission. Better-than-expected stability of the spacecraft clock has yielded adequate phase-analysis capabilities for extended observations of all sources with well known timing properties and has provided redundant capabilities for sources with periodic x-ray emission.

Ground-based observations of very high energy γ rays were reported by J. E. Grindlay with anomalous results from the Crab Pulsar. For primary γ -ray energies greater than 8×10^{11} eV, the pulse structure was found to be time-variable. The phase of the γ -ray pulse was found to vary from midway between the main and the secondary pulse to only 2 msec before the optical secondary pulse. For the Mount Hopkins observations, major instrumental sources of error were eliminated by repeated cross checks with observations of optical pulsations. Several other of the

groups making ground-based observations supported the Mount Hopkins results. The apparent intensity levels for high energy γ -rays were different for different groups and different observing times leading Grindlay to conclude that this emission is variable in both time and amplitude. Most agree that this high energy flux lies one to two orders of magnitude below a spectrum extrapolated from measurements at energies less than 1 GeV. However, preliminary results, presented by H. S. Tornabene in a hot topics session, indicate higher flux levels even during the same time period.

Grindlay reported very high energy observations of only one other pulsar. An Australian group at Narrabri found a single-peak pulse from Vela in contrast with the double peak structure at energies near 100 MeV, but strikingly similar to the Crab which changes from double to single pulse structure at the highest energies.

P. A. Sturrock presented predictions based on a pulsar model in which high energy γ -rays interact with the intense magnetic fields in pulsar magnetospheres (10^{12} gauss) to produce electron-positron pairs. Radio emission results from charge bunching, which is caused by instabilities in the electron-positron streams. The predictions of this model are consistent with the observed period-age distribution for radio pulsars and the observed spectral index in the γ -ray range of the spectrum. The model however, would not permit 10^{12} eV γ rays to escape through the intense polar-cap magnetic fields, and would not explain the apparent phase and amplitude variations at γ -ray energies. One prediction for which appropriate observations may soon be available is that the x-ray emission should be polarized and orthogonal to the optical polarization.

Besides the pulsar observations, evidence for several other sources of high energy γ rays was reported. Both the COS-B and the SAS-2 data show enhanced γ -ray intensity in the region of the galactic anticenter, $l^{\text{II}} = 195^{\circ}$, $b^{\text{II}} = 5^{\circ}$, which has not been identified with any known object. Cyg X-3, an x-ray source with a 4.8-hour period, was observed in the SAS-2 data and at very high γ -ray energies from ground based observations. The peculiar radio galaxy Cen A has also been detected up to energies of 10^{12} eV. Many fundamental questions await future observations with improved sensitivities in both space and ground-based instrumentation.

LOW ENERGY GAMMA RAYS

Low energy galactic γ -rays carry information on hadronic interactions of low energy cosmic rays and on bremsstrahlung radiation of cosmic ray electrons. This portion of the electromagnetic spectrum was the subject of nearly half of the presentations at the symposium in 1973. New observations of the diffuse γ -ray continuum and of γ -ray lines from solar flares sustained a wave of theoretical interpretation and speculation. The lack of any new satellite observations at energies below 30 MeV since that time is reflected in their much smaller share of the present proceedings.

The outlook for future observations, however, is far more encouraging than the lack of new data is discouraging. G. H. Share presented a detailed and informative summary of current detection techniques including an evaluation of their capabilities for measuring the diffuse γ -ray continuum and γ -ray lines. He concluded that we can expect to learn much more about diffuse galactic radiation in the 1 to 100 MeV range in the next few years. Spatial mappings are expected to approach the resolution achieved with SAS-2 at higher energies.

The detection of γ -ray line emission is reportedly promising both from the recent balloon observations of the galactic center reviewed by G. H. Share and from the theoretical predictions presented by R. E. Lingelfelter. Both balloon observations and the Apollo measurements reported by J. I. Trombka in a hot topics session give tentative evidence for line emission at 4.4 MeV. Although the observed intensities are higher than those predicted by earlier calculations, the spectral features at 0.51

and 4.4 MeV are expected from positron annihilation and from the decay of $^{12}\text{C}^*(4.4 \text{ MeV})$. At the present time, uncertainties in detector backgrounds affirm the need for more sensitive observations before a non-cosmic origin of these lines can be ruled out. R. E. Lingenfelter presented calculations of the production rate of the 4.4-MeV line, taking into consideration a few more nuclear processes than in previous calculations but more importantly considering spatial variations in cosmic-ray density. He finds that the observed 4.4-MeV line intensity from the galactic center is consistent with a low-energy cosmic-ray density which increases toward the galactic center in proportion to the molecular gas density.

With the advent of high resolution solid state detectors in orbit, the first of which were reported at the symposium in 1973, details of γ -ray line spectra can be studied. An exciting new suggestion by Lingenfelter and Ramaty is that γ -ray lines may be produced by cosmic ray interactions with ambient material concentrated in dust grains. The kinematic recoil of excited nuclei in dense media may be slowed, providing the life time of the excited state is sufficiently long, eliminating the Doppler broadening of the line otherwise expected. Studies of the narrow component in each nuclear excitation line will provide a measure of the nuclear composition and spatial distribution of grains in the galaxy. The most promising nucleus for such observations is ^{16}O with an excited state at 6.1 MeV that is longer lived than the 4.4-MeV level in ^{12}C . Supernova explosions were suggested as another possible source of γ -ray line emission by W. D. Arnett. Observations of the relative line intensities from supernovi would test current models of thermonuclear processing and stellar structure.

SUMMARY

The mood of the participants at the end of the symposium was best characterized by K. Greisen's remark during the panel discussion. He needed time to digest the new results and to assess their physical significance. But without hesitation he declared that SAS 2 and COS B are "marvelous"! And he was looking forward to seeing the results of more observations.

The panel discussion comprised comments on both the instrumental and the theoretical outlook for γ -ray astronomy and galactic astrophysics. E. N. Parker noted that the problem of how to inflate the galactic halo, an important ingredient in models of cosmic-ray confinement, was not yet solved. C. Fichtel and V. Schönfelder both emphasized the need for much more sensitive γ -ray instruments to overcome the severe limitations imposed by the low fluxes of energetic γ rays. For the study of the diffuse γ -ray continuum and γ -ray lines, J. I. Trombka noted that new types of instrumentation and dedicated satellites are needed to overcome the background rates which have been observed for low-energy γ rays. E. I. Chupp agreed and added that a great deal of astrophysical information will be contained in data from the low-energy, nuclear-transition region of the γ -ray spectrum.

The symposium concluded with the Goddard Space Flight Center Colloquium presented by K. Greisen. Greisen identified the variability in the phase of the Crab pulsar at the highest γ -ray energies as the most intriguing observational puzzle. Also important to an understanding of the pulsar mechanism are measurements of the polarization of the hard x-ray

and γ -ray emission, which should exist if Sturrock's model is correct. With respect to the γ -ray measurements and galactic structure, Greisen noted that the spiral structure interpretation is not really confirmed by radio measurements and that a model based on the molecular hydrogen distribution works exceptionally well. Unambiguous distinction between these models requires better measurements of the molecular hydrogen distribution. As was pointed out by Scoville, no property of the interstellar medium in the vicinity of the galactic ridge is certain to better than a factor of 2 except possibly for galactic scale heights; however, Parker was quoted as remarking that scale heights are also uncertain. Clearly much recent progress in γ -ray astronomy has stimulated interest and enthusiasm for studies of galactic structure. This progress has also provided a solid foundation from which to continue and to extend exploration by γ -ray observations.

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R. Buccheri - Università di Palermo, Italy
W. B. Burton - National Radio Astronomy Observatory, Greenbank, USA
G. G. Fazio - Harvard College Observatory and Smithsonian Astrophysical
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K. Greisen - Cornell University, USA
J. E. Grindlay - Harvard College Observatory and Smithsonian Astrophysical
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E. B. Jenkins - Princeton University, USA
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H. A. Mayer-Hasselwander - Max Planck Institute, Munchen, West Germany
H. Ogelman - Middle East Technical University, Ankara, Turkey
E. N. Parker - University of Chicago, USA
J. A. Paul - CEN Saclay, France
J. L. Puget - Observatoire de Meudon, France
W. W. Roberts, Jr. - University of Virginia, Charlottesville, USA
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