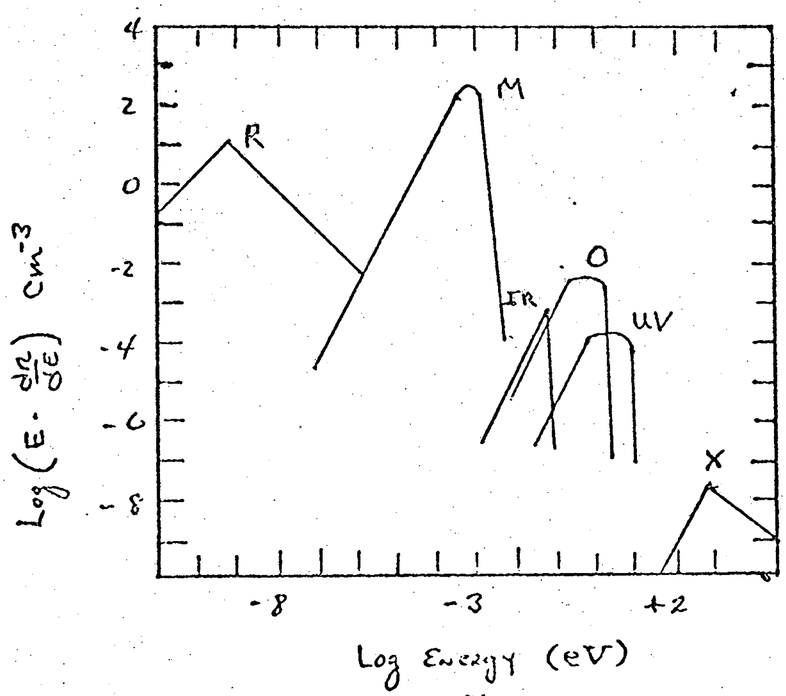
X-RAY AND GAMMA RAY ASTRONOMY

R. L. Brown

I. Cosmic Photon Spectrum

A. From observations of cosmic radio sources we know that the universe is filled with photons which have energies as low as 10^{-8} eV; while from cosmic ray extensive air showers it can be inferred that photons with energies exceeding perhaps 10^{22} eV are also present. The cosmic electromagnetic spectrum can be derived both from direct observations where possible (radio, microwave, X-ray) and from extrapolations into the unobservable regions with the help of theoretical models. Doing this one finds (Gould 1968, Annual Reviews of Astronomy and Astrophysics, 6, 195)



B. The radio flux (R) is due to a superposition of flux from sources out to the Hubble radius, at microwave energies (M) the emission is dominated by the 3° K blackbody radiation whose energy exceeds all other contributors; the infrared (IR) region reflects largely 12.8μ emission from the $2P_{3/2}-2P_{1/2}$ transition in Ne^+ from H II regions in all galaxies; the optical (O) radiation is due to cool stars while the ultraviolet (UV) is due to the integrated flux of young stars.

C. It is easily observed that the X-ray (∿ 13.6 eV-1 MeV) and γ-ray (> 1 MeV) contributions to the total photon spectrum are certainly miniscule when compared to the others. Much can be learned, however, from a study of this region.

II. History of X-ray and γ-ray Astronomy (cf. Friedman 1968, in Stars and Stellar Systems, vol. 7)

A. It has often been said that the discovery of extra-solar X-rays was totally unexpected: This is largely because most of our previous astronomical knowledge resulted from efforts directed toward observation of optical photons and presented a prejudiced view of the constituents of the universe.

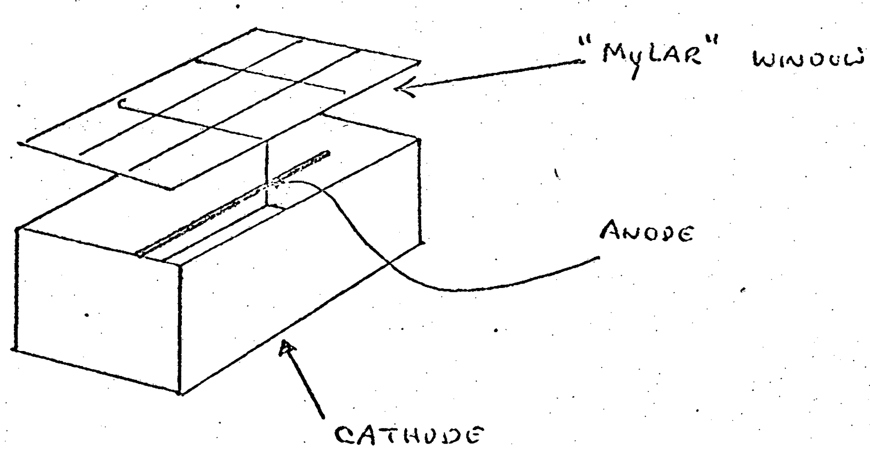
B. X-ray astronomy is still so young that one may start with the earliest observations. A scintillation counter flown in 1956 indicated the presence of a non-solar component to the X-ray flux at keV energies, but the data was not convincing.

C. In June 1962 a group from NRL flew an X-ray proportional counter in an attempt to detect X-rays from the moon presumably excited by fluorescence as stimulated by solar X-rays. They failed to detect lunar X-rays but noticed a strong source slightly displaced from the moon; analysis showed this source to be nearly coincident with the galactic center. From this observation, X-ray astronomy was born--just eight years ago!

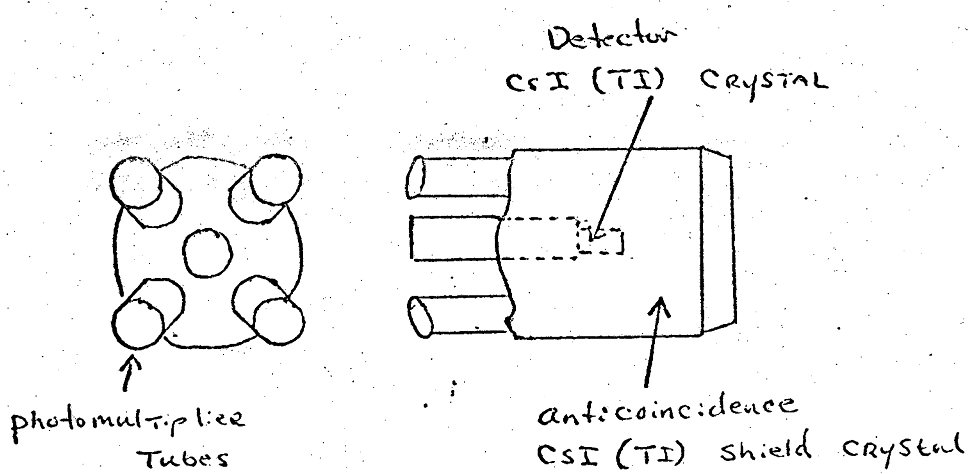
III. Detectors

A. Because of the enormous energy range ($\sim$ 20 decades) several different techniques must be used to make the required measurements.

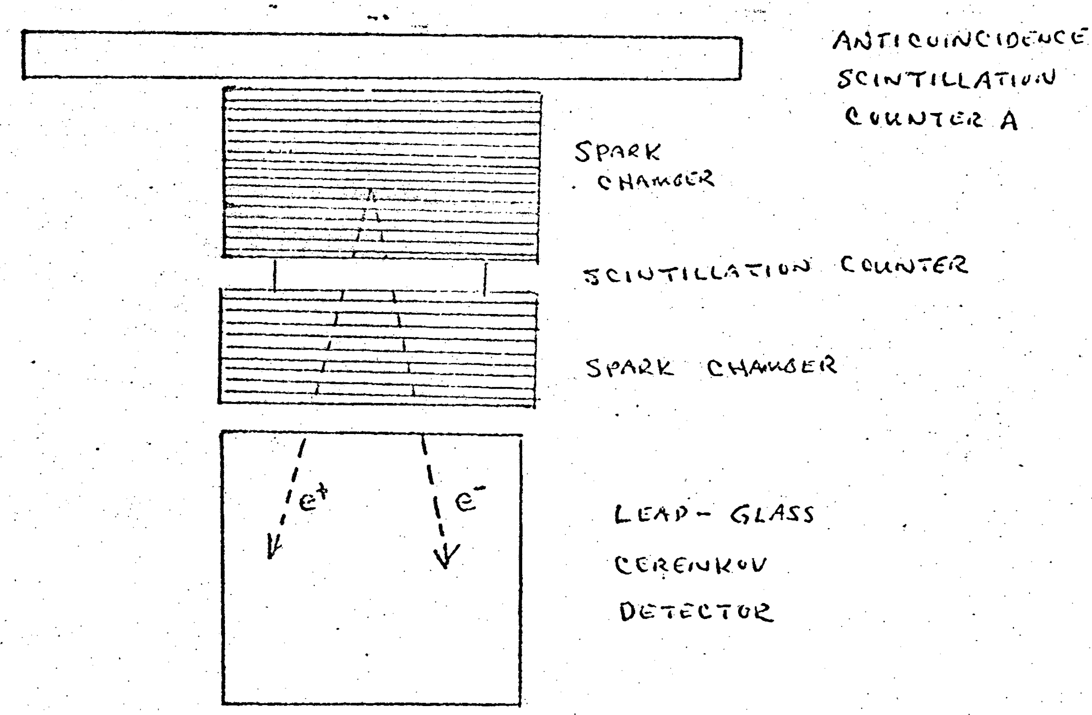
B. Proportional Counters: (0.1 keV < E < 10 keV). This is essentially a Geiger counter consisting of a gas with electrodes arranged so that a high electric field gradient is obtained near the cathode. An X-ray photon is absorbed in the counter gas (argon-methane), ionizes an atom and ejects a photoelectron which causes further ionization and produces a cloud of electron-ion pairs. This cloud drifts toward and is collected on the anode: The total charge is proportional to the number of electrons and provides a measure of the photon energy. Schematically (Giacconi et al. 1968, Annual Reviews of Astronomy and Astrophysics, 6, 373),



C. Scintillation Detectors: (10 keV < E < 10 MeV). This detector is essentially a scintillation crystal, NaI (Tl) or CsI (Tl), in which a high energy γ ray converts its energy to electron-positron pairs. These pairs radiate bremsstrahlung photons which are recorded by a photomultiplier tube mounted directly behind the crystal. As the PM output is proportional to the number of e^{+}-e^{-} pairs, and these are in turn proportional to the energy of the incident γ ray, one can obtain some energy resolution. The whole detector is usually shielded from charged particles by another scintillation counter used as an anti-coincidence shield.



D. Scintillation-Cerenkov Counters and Spark Chambers (10 MeV < E < 10 GeV). In this energy region a gamma ray photon is detected by the electron-positron pair it produces when interacting with matter. The most recent such detector uses spark chambers both to convert a γ ray into electron-positron pairs and also to make visibile the paths of the pairs; this apparatus is followed by a Cerenkov detector which permits energy measurements to be made. The spark patterns are recorded photographically and provide relatively good angular and energy resolution. Schematically (Fazio 1967, Annual Reviews of Astronomy and Astrophysics, 5, 481),



E. Detectors for Photon Energies > 10^{10} eV. Gamma ray photons with energies exceeding 10^{11} eV can be detected only by the cascade of particles they produce upon interaction with the atmosphere. The reaction is initiated by an electron-positron pair that produces additional photons, e^+, e^- by bremsstrahlung, Compton scattering, and pair production. The cascade shower can be detected on the ground either by looking at the Cerenkov radiation produced by the shower or by use of a large array of scintillation counters to detect the arrival of a burst of charged particles in the shower.

IV. Observational Data

A. Discrete Sources. There have presently been identified approximately sixty discrete X-ray sources (Dolan 1970, A. J., 75, 223) having fluxes in the range 20-0.2 photons/cm^2-sec-ster-keV for energies 1-40 keV. Five of these sources have also been seen at γ-ray energies. The sources seem to group in two broad clusters; one is an association in the Cygnus-Cassiopeia region (ℓ^{II} 60°-120°) within an average of ± 7° from the galactic plane--the suggestion here is that they lie in the Orion-Cygnus arm of which the sun is a member at an average distance of ∿ 1 kpc. The other group occurs in the direction of the galactic center again predominantely in the plane; assuming that these sources lie in the Sagittarius arm their distance is ∿ 2 kpc.

Due to the low flux levels which can be currently observed, only two sources have had their spectra studied in any detail (Sco X-1 and Tau X-1), but these seem to be representatives of two general classes of X-ray sources.

Sco X-1. Sco X-1 is the brightest X-ray source in the sky and has been optically identified with a very peculiar blue starlike object of magnitude 12.5. The optical characteristics suggest that the object is an old or recurrent nova. The X-ray spectrum is well reproduced by thermal bremsstrahlung emission at a characteristic temperature of around 50 million degrees. Such a spectrum would account both for the very blue optical continuum and the radio emission which has been detected at the proper level at 3.7 and 11 cm. The entire spectrum is subject to large scale variations ($\sim$ 10 percent) on a time scale of weeks and a pronounced flickering is also present at much shorter intervals.

Tau X-1. The Crab Nebula has also been extensively studied in the X-ray; the picture which emerges is that of a synchrotron source with the same spectral index that is observed in the optical region, $\sim$ 1.5. A long-standing problem associated this explanation has been that of replenishing the synchrotron electrons which presumably produce this X-radiation: Their lifetime is $\sim$30 years whereas the nebula is $\sim$1000 years old. This problem has either been solved or re-directed (depending on your own faith) with the discovery of the pulsar in the Crab. In this respect, approximately 10 percent of the X-rays from the Crab have been identified as coming from the pulsar (by a lunar occultation experiment) and this component does in fact show the pulse structure with the same shape and period as is derived from the radio data.

All the other discrete X-ray sources for which moderately good data exist suggest that they either have an exponential-type bremsstrahlung spectrum (as Sco X-1) or the power law synchrotron spectrum as is found in the Crab. Much further observational data is needed however.

B. Diffuse Background. In addition to localized discrete sources, a general background of x- and γ-rays has been observed from 0.25 keV to 100 MeV. Isotropy measurements show this background to be isotropic to better than 5 percent and thus it is inferred that the diffuse X-rays are extraglactic. As a very good approximation the background can be represented by two power laws, the spectrum flattening at lower energies:

$$j(E) = \begin{cases} 9.8\ E^{-1.6} & \text{photons/cm}^2\ \text{sec ster-keV} \quad E \lesssim 30\ \text{keV} \\ 135\ E^{-2.4} & \text{photons/cm}^2\ \text{sec ster-keV} \quad E \gtrsim 30\ \text{keV} \end{cases}$$

V. Diffuse Cosmic X- and γ-Ray Background: Theory.

A. Theory of the X-ray Background. Since the diffuse background high energy photons are neither deflected by magnetic fields nor substantially absorbed in reaching us, they can be used as a sensitive tool to examine the large-scale structure of the universe. Essentially two types of mechanisms have been proposed to explain the X-ray background; each involves well understood processes for photon production which must occur between particles and an ambient gas or between particles and radiation. In one case interactions between these components in the intergalactic medium is proposed whereas in the other the integrated effect of discrete sources is invoked.

(a) Discrete source models (Silk 1968, Ap. J., 151, L19).

This model assumes that all ordinary galaxies contain a mixture of Sco X-1 and Crab-type X-ray sources and that they evolve in a manner similar to that observed in strong radio sources. The spectral features presumably are a result of a superposition of the two types of galactic sources making contributions at different energies.

(b) Inverse Compton scattering in discrete sources (Bergamini et al., 1967, Nuovo Cimento, 52B, 495). Here it is proposed that a large flux of X-rays is generated by Compton scattering of fast electrons on the microwave background radiation inside strong radio sources at very early times in the evolution of the universe ($z \sim 5$). However, in order not to produce an inordinately large radio background they must assume magnetic fields inside sources of the order of 10^{-6} gauss, a value far below that inferred from radio data.

(c) Inverse Compton scattering in the intergalactic medium. (Felten, 1963, Phys. Rev. Letters, 10, 453, Brecher 1969, Phys. Rev. Letters, 23, 802). In this case it is assumed that the same electrons which produce the radio flux of strong radio galaxies by synchrotron radiation, eventually escape from the galaxy and undergo inverse Compton scattering on the microwave radiation in the intergalactic medium and thereby produce the X-ray background. However, without the use of several ad hoc assumptions the intensity derived is two orders of magnitude too low, although the spectral shape does in fact agree with that observed.

B. Theory of Gamma Ray Background. The existence of high energy cosmic photons is inferred from measurements of high energy cosmic rays. Assuming that the bulk of cosmic rays are protons, these particles in traversing the intergalactic or interstellar gas, can collide with atomic nuclei and produce a number of high energy pions; the neutral pions decay directly into photons while the charged pions decay into muons, electrons and neutrinos.

The high energy electrons from the π-μ-e decay can then produce, for example in being scattered by another nucleus or electron, a Bremsstrahlung photon of any energy from zero up to the initial energy of the electron. Moreover, since the bulk of the emission from strong radio sources is by synchrotron radiation from high energy electrons in magnetic fields, these electrons must also be producing high energy photons.

C. Is There a Maximum Photon Energy? The cosmic gamma ray spectrum will be attenuated by electron-positron pair production through interaction of the high energy photon γ_h with other ambient photons γ_a,

$$\gamma_h + \gamma_a \rightarrow e^+ + e^- \quad .$$

The thresholds for this reaction are 10^{12} eV when γ_a refers to optical photons, 10^{14} eV when γ_a is a microwave photon and 10^{20} eV when γ_a refers to radio photons. Accordingly, there should be few photons above 10^{20} eV (cf. Gould 1967, Phys. Rev. Letters, 16, 252).

VI. Future Expectations

(a) There now exist marginal X-ray detections of the strong radio galaxies Cyg A, M87, and Centaurus A. When these detections can be confirmed with much lower errors it will be possible to unambiguously establish the value of the magnetic field in these radio sources without recourse to the conventional equi-partition arguments. Assume the X-ray radiation is a result of inverse Compton radiation in the sources from an electron distribution $N(E)dE = KE^{-\gamma}\, dE$, then the flux is

$$F_x \propto KE_x^{-\gamma} .$$

The radio radiation is due to synchrotron radiation so,

$$F_R \propto H^{\gamma + 1/2} KE_R^{-\gamma}$$

so that knowing the ratio of these quantities provides a direct measure of the magnetic field H.

(b) With detectors of sufficiently narrow energy resolution the K-shell ionization edges of the atomic species present in the interstellar medium could be observed and therefore an unambiguous determination of the atomic abundances in the interstellar medium could be made.

(c) If provided with sufficient angular resolution and sensitivity, one could resolve whether the diffuse background is being produced by discrete sources or rather in a continuum process operating in the intergalactic medium.