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MASTER

X-Ray and Gamma-Ray Astronomy

The earth's atmosphere strongly absorbs most electromagnetic waves that reach our planet from outer space. In this opaque screen there exist only a few windows, of which the most important - as far as life on earth is concerned - extends from about 3000 to about 7000 Ångstrons (one Ångstrom is 10^{-8} cm; i.e, there are one hundred million Ångstroms in one centimeter). The fact that these wavelengths correspond roughly to the limits of the spectrum of visible light means that the human eye and that of the other higher animals is sensitive to the radiations that pass through this window. This coincidence is certainly not due to chance; it is rather the result of natural selection, which favored the development of organisms capable of using solar rays that reach the surface of the earth for the purpose of finding their way in their surroundings. As a by-product of natural selection, mankind found itself endowed with an instrument by means of which it could observe celestial objects through one of the windows in the atmosphere. Indeed, from ancient times almost to present days, practically everything that man learned about the structure of the universe was the result of observations with visible light.

There are no other windows on the short-wave side of the optical window. On the long-wave side, however, there are several narrow windows in the infrared, and one rather wide window in the spectral region of radio waves. The latter extends from a minimum wavelength of the order of one centimeter to a maximum wavelength of several

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tens of meters. The lower limit is determined by the absorption of oxygen and water vapor, the upper limit by the absorption of free electrons in the ionosphere.

Several years ago, technical developments in the field of radio communications enabled man to look at the sky through this window. I cannot dwell here on the far-reaching changes in our ideas about the surrounding world brought about by radio astronomy. Among other things, where the telescope of classical astronomers had seen a universe populated by isolated celestial bodies moving in an essentially empty space, the antenna of the radio astronomer perceived an entirely different picture. Rather than the stars, there appeared now in the foreground the interstellar space itself filled with very thin gases, with fast electrons, with magnetic fields.

To-day space vehicles provide astronomers with the opportunity of observing, free from any atmospheric obstacle, the whole spectrum of electromagnetic waves reaching the earth. A new chapter in the history of astronomy is thus about to open, and there is no doubt that we shall witness another fast and perhaps revolutionary development in our knowledge of the universe. This prediction is based in part upon the existence of important astronomical problems that to-day, for the first time, become accessible to a direct experimental investigation; but it is based mainly on the well-tested fact that nature is more imaginative than man and has always surprises in store for the scientist who first ventures into unexplored ground.

In what follows, I shall talk sometimes of radiations of a given wavelength, sometimes of photons of a given energy. The two expressions are equivalent, for it is well known that the energy of electromagnetic radiation is quantized and that the magnitude of the radiation quantum is inversely proportional to the wavelength.

To begin with, let us examine in more detail the atmospheric absorption of electromagnetic radiation of different wavelengths. This is illustrated in Fig. 1 ; plotted on the horizontal axis are the photon energies in electron-volts (eV) and the corresponding wavelengths in meters, centimeters or Ångstroms; plotted on the vertical axis is the height above sea level in kilometers and also the fraction of the atmospheric mass above each given height. The curves represent the atmospheric levels where the intensities of rays with different photon energies are reduced to 1/2, 1/10 and 1/100 of their initial values. The graph shows, for example, that photons with energies of several thousands eV (which belong to the spectral region of soft x-rays) can be observed only at altitudes greater than about 80 km, such as can be reached by rockets or artificial satellites.

At first glance it would seem that photons of greater energy (i.e., photons belonging to the spectral regions of hard x-rays and γ-rays) should be detectable at much lower altitudes. However, in these spectral regions, secondary radiations produced in the atmosphere by cosmic rays seriously interfere with the observations, even at altitudes where the attenuation is relatively small. The situation changes only at energies greater than 10^{12} or 10^{13} eV; in principle, at least, rays of these exceedingly high energies can be detected even at moderate altitudes by means of the "showers" of secondary particles which they produce in the atmosphere.

Beyond the terrestrial atmosphere lies the interplanetary space, occupied by a very dilute ionized gas, mostly hydrogen, with a mean density of several ion pairs per cm^3. Electromagnetic waves of all wavelengths, up to a maximum value of several kilometers, can traverse the interplanetary medium with practically no absorption. Thus, once out of the atmosphere and the ionosphere, nothing interferes with the observation of radiations originating from the sun or the planets. Quite naturally the sun was the first celestial object to which space astronomers directed their attention. They found, among other things, that the sun is a source of x-rays whose intensity, unlike that of light, varies over a very wide range with changing solar activity, although it is always a very minute fraction of the light intensity.

The sun is one of the 100 billion stars that form our galaxy. Most of these, particularly the young ones, are contained in a flast disk with a thickness of the order of 1000 light years and a diameter of the order of 100.000 light years. The space between the stars in the disk is filled with a gas consisting again mainly of hydrogen but, for the most part, in the form of neutral atoms. Its density is somewhat smaller than one atom per cm^3. The galactic disk is surrounded by a nearly spherical halo consisting mainly of old stars, where the gas density is much lower than in the disk.

Galactic distances are so great that the interstellar gas, despite its extreme dilution, can absorb appreciably radiations of certain wavelengths originating from celestial objects outside the solar system. The absorption of interstellar gas is illustrated in Fig. 2. Here again, as in Fig. 1, both photon energies and wavelengths are shown on the horizontal axis; while on the vertical axis is now plotted the distance (in light years) from a given source to the earth, multiplied by the average density of interstellar gas along the path (in atoms per cm^3).

One then sees that, for galactic distances, the absorption of interstellar gas is negligible all the way from the radio waves to ultraviolet rays of 912 Å wavelength. At this wavelength, which corresponds to a photon energy of 13.5 eV., the interstellar gas suddenly becomes very opaque. This is due to the fact that 13.5 eV is the energy needed to ionize hydrogen atoms so that, beyond this energy, photons are rapidly absorbed in the process of ionizing interstellar hydrogen. As the energy increases further, the probability of ionization of hydrogen decreases and, so does the absorption of photons through this process. The gradual decrease of absorption with increasing energy is interrupted by discontinuities occurring at the ionization energies of helium and of the other less abundant components of interstellar gas. Eventually, at energies greater than several thousand eV, i.e., at wavelengths smaller than a few Ångstroms, the absorption of interstellar gas over galactic distances becomes again negligible.

Besides gas, the galaxy contains also a certain amount of dust, concentrated near its equatorial plane. Starting from the infrared, the dust produces an appreciable absorption, which first increases, then decreases, with decreasing wavelength. For wavelengths smaller than 912 Å, however, the absorption of dust is negligible compared with that of interstellar gas.

In what follows, I shall confine my remarks to radiations from extrasolar sources, belonging to that portion of the spectrum that lies on the short-wave side of the "blind region" due to the absorption of interstellar gas; these radiations include x-rays and gamma-rays.

X-rays and gamma-ray astronomy is still in its infancy. So far, scientists have made preliminary investigations of only a few small portions of the enormous spectrum ranging from several hundred eV (where interstellar gas becomes again transparent) to energies of the order of 10^{14} or 10^{15} eV (the highest energies that one may hope to reach by the use of air-shower techniques). Here I shall discuss only two groups of experiments. These are 1) some experiments on x-rays of several thousand eV energy - the only experiments for the moment that have revealed the existence of previously unknown celestial radiations, and 2) some experiments on gamma-rays of about one hundred million eV energy which, without giving clearly positive results, afforded neverthless some interesting conclusions.

I shall start with the latter group of experiments, among which the most precise are those carried out by Kraushaar and Clark of the Massachusetts Institute of Technology.

To appreciate the significance of these experiments, I would like to point out that, for what we know, the only important source of photons with energies above some tens of millions eV is the spontaneous decay of π^0-mesons. The π^0 -meson is a neutral particle that can be produced in high-energy nuclear interactions as well as in the annihilation of protons or neutrons with antiprotons or antineutrons. Its decay products are two photons:

$$\pi^0 \rightarrow \gamma + \gamma$$

and its mean life is of the order of only 10^{-16} seconds.

π^0 -mesons and, therefore, high-energy γ-rays are certainly generated in our galaxy as a consequence of collisions of primary cosmic rays (which are mainly high-energy protons) with the nuclei of hydrogen and of the other atoms found in interstellar space. The computed spectrum of these γ-rays has a maximum around 50 million eV; it drops rapidly to zero toward the small energies and falls off more slowly toward the high energies.

The solar system is located near the galactic equator. Therefore, at the earth, the γ-rays produced in the manner described above should arrive with maximum intensity from directions close to the galactic equator - i.e. from the Milky Way.

Interstellar gas is so diluted that a cosmic-ray proton has only one chance in several hundred to undergo a collision over a distance equal to the diameter of the galaxy. Therefore, the intensity of γ-rays arising from such collisions is very small. It has been computed, for example, that a spherical detector with a cross-section of 10 cm^2 would count α-rays produced by π^o -decay at a rate of about 2 per minute; whereas a cosmic-ray detector of the same size would count about 7000 particles per minute.

The measurements of Kraushaar and Clark were performed by means of a satellite - Explorer XI-launched in March, 1961. The "γ-ray telescope" used by these scientists (see Fig. 3) took advantage of the fact that, in passing through matter, γ-rays of the energy here considered undergo a materialization process, giving rise to pairs of fast electrons (positive and negative). The difficulty, of course, was that of distinguishing γ-rays from the much more abundant ordinary cosmic rays. The instrument achieved this purpose by making use of the fact that cosmic-ray particles leave a trail of ions all along their paths, while γ-rays begin to ionize only at the moment when they change into electron pairs (see Fig. 4).

Using this criterion and various other devices to suppress spurious effects Kraushaar and Clark observed what seemed to be a small γ-ray flux of celestial origin. This flux was about ten times greater than that computed. This discrepancy in itself, was not serious, because of the uncertainties in the computations due to a large extent to our imperfect knowledge of the average density of interstellar matter. More disturbing was the observation that the presumed γ-rays came from all directions, and not preferentially from the galactic plane. This, of course, does not necessarily mean that the observed effect is due to spurious causes; it is possible, for example, that, in addition to galactic γ-rays, there exist γ-rays of extragalactic origin, more abundant than the former and distributed isotropically. However, in the absence of an anisotropy, it is advisable to reserve judgement and use the results of Kraushaar and Clark only to set an upper limit to the flux of γ-rays incident upon our planet.

Further experiments, with improved equipment, are in preparation by Kraushaar and Clark as well as by other scientists. But this upper limit is already of great cosmological significance in the following context. Many scientists believe that, while the universe expands, new matter is created in space so that the mean density of the universe remains constant. Moreover, some have suggested that the new matter may appear in the form of proton-antiproton pairs. This hypothesis is now ruled out by the experiment described above. For the antiprotons born in our galaxy, colliding against the ordinary protons found in interstellar space, ought to undergo annihilation, thereby producing π^o-mesons. According to the computations, the decay of such mesons would produce a flux of γ-rays about 500 times greater than the upper limit set by the experiment of Kraushaar and Clark.

I shall come next to the experiments on x-rays which, as I already mentioned, are the only ones so far that have produced clearly positive results. Three research teams have taken part in this work; one at American Science and Engineering (Giacconi <u>et al</u>); one at the Naval Research Laboratory of Washington (Friedman <u>et al</u>); one at Lockheed (Fisher <u>et al</u>). All experiments were carried out with rockets launched vertically to a maximum height of over 200 km, which gave useful observation times of about 5 minutes. The detectors were either Geiger counters or proportional counters, with very thin windows opaque to light and ultraviolet rays but transparent to x-ray photons down to fairly low energy. Indeed, these detectors had maximum sensitivity for photons of several thousand eV energy (i.e., for x-rays of several Ångstroms wavelength). To reduce the cosmic-ray background, Giacconi had used the fact that x-rays stop in the counter while cosmic rays go clear through it; Friedman and Fisher, on the other hand, had taken advantage of the difference in size between the pulses produced in a proportional counter by x-rays and by cosmic rays. One should notice that these criteria did not rule out electrons of moderate energy which, if present in sufficient numbers, might have interfered with the experiments. In his latest flight, Giacconi used also two scintillation counters, of which one was sensitive to photons with energy greater than about 8000 eV and electrons with energy greater than about 30,000 eV, while the other had the same response to electrons, but was practically insensitive to photons.

Fig. 5 shows, as an example, the instrumentation of one of the rockets used by Giacconi and his collaborators.

The interpretation of the results reported by Fisher's group is still doubtful, mainly because of their low statistical accuracy. Therefore, I shall confine my discussion to the results of the other two groups.

These results, which check and supplement each other, have demonstrated the existence of one strong celestial source of x-rays and, in all likelihood, of two additional sources of smaller strength. Moreover, they have suggested the existence of a diffuse x-radiation coming apparently from all directions. The positions of the three sources are shown on the map of the sky that appears in Fig. 6.

Let us consider first the main source (X-1). This source was seen for the first time by ~~the~~ Giacconi's team in June 1962, with two counters of high sensitivity but low angular resolution. The rocket was spinning around a vertical axis, and Fig. 7 shows the angular dependence of the counting rates of both counters. The very pronounced maximum obtained with the more sensitive counter, and the less pronounced maximum obtained with the less sensitive counter, are due to the passage of the source through the fields of view of the two instruments.

The same source was seen, in April 1963, by Friedman's team, using a detector with a narrower field of view, and having, therefore, smaller sensitivity but better angular resolution; these measurements yielded the most precise data on the position of the source; moreover, they proved that its angular dimensions do not exceed about 5^{o}. Source X-1 was seen for the third time by Giacconi in June 1963, both with a Geiger counter and with the scintillation counter sensitive to photons.

From the results of their first flight, Giacconi and his co-workers were able to conclude (through a set of arguments which I cannot develop here) that the observed radiation consisted of x-rays rather than electrons. Moreover, in their latest flight, they obtained direct confirmation of this conclusion from their observations with the two scintillation counters.

In all three experiments the source was sufficiently high above the horizon to rule out an atmospheric origin. Moreover, X-1 was observed at three different times in the same position relative to the fixed stars, and in a control experiment performed by Giacconi in October 1962, when X-1 should have been under the horizon, no x-ray source of intensity comparable to X-1 was in fact detected.

The data concerning the other two sources (X-2 and X-3) are less complete and their interpretation is perhaps somewhat less certain. X-2 was observed, although not as clearly as X-1, in all three flights of Giacconi. In the observations made with Geiger counters in June 1962 and June 1963, X-2 was held responsible for an asymmetry in the main peak of the curve of counting rate vs. azimuth (see Fig. 7); in the observations made in October 1963, the presence of X-2 was indicated by a small separate peak; X-2 gave rise also to a separate peak in the curve obtained in June 1963 with the photon-sensitive scintillation counter. X-2 was not seen by Friedman because it was below the horizon at the time of his flight.

The existence of X-3 had been suggested by the presence of a small peak in the azimuthal distribution of counting rate obtained by Giacconi in October 1962. In April 1963 Friedman produced more conclusive evidence for its existence and was also able to show that its position coincided with that of the Crab Nebula, within the experimental uncertainty of a few degrees. X-3 was below the horizon at the time of Giacconi's flights in June 1962 and June 1963.

Nothing that was previously known about physical processes occurring in celestial bodies made it possible to foresee the existence of x-ray sources at the observed strength. And, indeed, the nature of these sources is still a matter of speculation. Before mentioning some of the hypotheses that have been put forward, I would like to present some general considerations that may help to explain why the discovery of such sources was received first with a certain amount of skepticism, then with considerable interest.

In the first place, the strength of the observed sources is remarkably great. The energy flux reaching the earth from X-1 in the form of x-rays with wavelength less than about 10 Ångstroms is of the order of 10^{-7} erg/cm^{2}sec. In the same spectral region the energy flux from the quiescent sun is only 10 to 100 times greater. At the time of large solar flares, the x-ray flux from the sun can temporarily reach values from 100,000 to one million times greater than that of X-1; but even if X-1 were a source as strong as the sun at the maximum of its activity, it would have to lie at a distance not greater than 1000 times that of the sun. This distance is about 3000 times less than that of Sirius, one of the nearest stars. This practically rules out any possibility that a source such as X-1 (or, for that matter, X-2 or X-3) may be a celestial body even distantly similar to the sun or to ordinary stars.

Another important fact to consider is that in the regions of the sky where the three x-ray sources were observed, there are no celestial objects of exceptional brightness. Thus the sources we are talking about must have the property of producing an abundant x-ray flux without producing at the same time a large flux of ordinary light; or else they must lie behind dust clouds of such thickness as to absorb light but not x-rays.

Coming now to the possible interpretations, it has been suggested recently by Chiu and by Friedman that the observed x-ray sources may be the so-called "neutron stars", about whose existence there had been much theoretical speculation but no experimental evidence. Supposedly, these stars are celestial objects of enormous density, formed almost entirely by neutrons, with a mass similar to that of the sun, but with a diameter of only 10 kilometers or so. They are supposed to be surrounded by a thin but opaque "atmosphere" of ordinary matter, at a temperature of about 10 million degrees, Kelvin.

It is well known that the maximum of the thermal emission spectrum shifts towards small wavelengths with increasing temperature, and reaches the spectral region of x-rays at a temperature of the order of 10 million degrees.

Thus, a body at 10 million degrees would be a powerful source of x-rays. Indeed, if it had the size ascribed to neutron stars, and were at a distance of the order of 1000 light years, it could send upon the earth an x-ray flux of the order of those arriving from the three observed x-ray sources. On the other hand, because of the small size, the emission of such an object in the spectral region of ordinary light would be so weak as to make it practically invisible.

It is believed that neutron stars may be born in those violent stellar explosions known as supernovae. In these explosions, part of the stellar material is blown off, giving rise to a rapidly expanding plasma cloud; while, at least in some cases, the remainder undergoes a catastrophic collapse, ending in a neutron star.

As I already mentioned, X-3 seems to coincide with the Crab Nebula, the remnant of a supernova that appeared in the sky the year 1054 and lies at a distance of about 3000 light years. Thus X-3 might be the hitherto invisible nucleus of this nebula.

If, on the other hand, the observed x-ray sources are not hot objects such as neutron stars, then it becomes necessary to assume that they contain fast electrons.

Electrons can radiate electromagnetic waves through three different processes. The first is ordinary bremsstrahlung (Fig. 8a). It occurs as a result of the deflection that electrons undergo in passing near atomic nuclei (in our case, the atomic nuclei in interstellar gas or in the somewhat denser matter found in some regions of space). The energy of the photons produced in this manner is often a substantial fraction of the energy of the primary electrons. Thus, in order to produce photons of several thousand eV, only electrons with energies of the order of 10,000 eV are needed.

The second process is the so-called inverse Compton effect (Fig. 8b). This is a process whereby a fast electron, colliding against a low-energy photon (i.e., a photon belonging to infrared rays or visible light), transfers part of its energy to the photon and brings it into the energy range characteristic of x-rays. In our case, the low-energy photons are those of ordinary star light. One can show that only electrons with energy greater than about 20 or 30 million eV can produce x-ray photons of the observed energy by the inverse Compton effect.

The third process is the so-called magnetic bremsstrahlung, whereby a fast electron radiates electromagnetic waves as a consequence of its deflection in a magnetic field. This kind of radiation has been observed experimentally in the synchrotrons, and therefore is also known as synchrotron radiation. Magnetic fields of several millionths of a gauss (microgauss) exist in interstellar space; it is believed that many of the signals detected by radiotelescopes are due to synchrotron radiation by fast electrons moving through interstellar space. However, only electrons of exceedingly high energy can produce x-rays via synchrotron radiation. For example, even in magnetic fields of 100 microgauss (which is much more than the average field strength in interstellar space) the necessary electron energy is greater than 10^{13} eV.

The question arises as to how electrons of sufficient energy to produce x-rays through one of the processes described above may be generated. One possibility is a direct acceleration mechanism due to time-varying magnetic fields associated with a plasma in a state of fast and disorderly motion - the same phenomenon held responsible for the acceleration of protons and other nuclei of the primary cosmic radiation. A second possibility is for high-energy electrons to be generated indirectly as a final product of nuclear interactions of protons accelerated by a similar mechanism.

Conditions favorable to the direct or indirect production of fast electrons occur in the clouds of magnetized plasma in a violent state of agitation that are produced by supernovae outbursts. Typical of these clouds is the Crab Nebula which has already been mentioned and which appears to coincide with X-3. According to some estimates, the Crab Nebula contains a magnetic field of the order of 100 microgauss. It contains electrons with energies of the order of 10^9 , whose synchrotron radiation produces strong radio noises; it also contains electrons with energies of the order of 10^{12} eV, whose synchrotron radiation produces a diffuse luminosity. The observed X-rays, too, may originate from electrons in the cloud ~~(perhaps through bremsstrahlung)~~ rather than from the hypothetical neutron star at the center of the cloud.

It is possible that the other two sources are also plasma clouds resulting from supernovae outbursts and containing high-energy electrons. In this case, however, there remains to explain why X-1, which is about ten times stronger than X-3, is not, like the Crab Nebula, a source of light and of strong radio signals.

Speaking of X-1, it has also been suggested that it may be the residue of an explosion, much more violent than a supernova, that would have occurred near the center of our galaxy some millions of years ago. Astronomers have recently detected in other galaxies explosions of this kind, apparently involving millions of stars.

These are only some of the possibilities under consideration. Clearly much more experimental work will be needed to determine the nature of the observed x-ray sources with any degree of certainty. It is particularly urgent to measure their spectrum, for different production mechanisms give rise to different spectra.

Moreover, interstellar absorption (see Fig. 2) produces, in the x-ray spectrum, a low-energy cut-off whose position depends critically on the distance of the source. Therefore, an experimental determination of this cut-off might tell us how far the observed sources lie.

Equally urgent is a measnrement of the angular dimensions of the sources, and a more accurate determination of their positions. When this is done, one will have to examine carefully whether or not there is any visible object (although not particularly conspicuous) or any source of radio noises (although not particularly strong) in the directions of X-1 and X-2.

Finally, it is necessary to see if there are sources of strength comparable to X-1, X-2 and X-3 in the regions of the sky that have not yet been explored; it is necessry to develop detectors of greater sensitivity to discover other possible weaker sources; and it is necessary to determine the origin of the diffuse x-ray background.

In conclusion, I would like to stress the fact that, while we have barely made a start in the new branch of astronomy discussed here, the results already obtained are extremely encouraging. For there is no longer any doubt that in the past the atmospheric screen, now eliminated by space vehicles, had prevented us from receiving celestial messages capable of revealing important and quite unexpected features of the surrounding universe.

Fig. 1. The absorption of the radiations of different wavelength, i.e., of photons of different energies, in the atmosphere.

Fig. 2. The absorption of radiations of different wavelengths, i.e., of photons of different energies, in interstellar gas.

Fig. 3. Gamma-ray "telescope" flown by Kraushaar and Clark on Explorer XI.

Fig. 4. How the γ-ray telescope shown in Fig. 3 distinguishes between high-energy photons and ordinary cosmic rays; (a) a cosmic-ray proton recorded by the detectors B and C produces a pulse also in detector A; (b) a photon produces pulses in B and C without producing a pulse in A.

Fig. 5. Instrumentation of the rocket flown in June 1962, by means of which Giacconi, Gursky, Paolini and Rossi detected for the first time extra-solar sources of x-rays.

Fig. 6. Mercator map of the sky showing the positions of the three x-ray sources X-1, X-2 and X-3. C is the center of the galaxy.

Fig. 7. Counting rates as a function of azimuth as observed by Giacconi et al. Open dots represent data obtained with the Geiger counter having a thinner window and, therefore, higher sensitivity; solid dots represent data obtained with the counter having a thicker window and, therefore, lower sensitivity.

Fig. 8. Three processes by which high-energy electrons can produce γ-rays: (a) Ordinary bremsstrahlung (a photon, γ, is produced in the passage of an electron, e, near an atomic nucleus); (b) inverse Compton effect (the collision of a high-energy electron, e_1, with a low-energy photon, γ_1) results in a high-energy photon, γ_2, and a low-energy electron, e_2); magnetic bremsstrahlung (an electron, e, in a magnetic field, gradually loses energy by emitting photons, γ).

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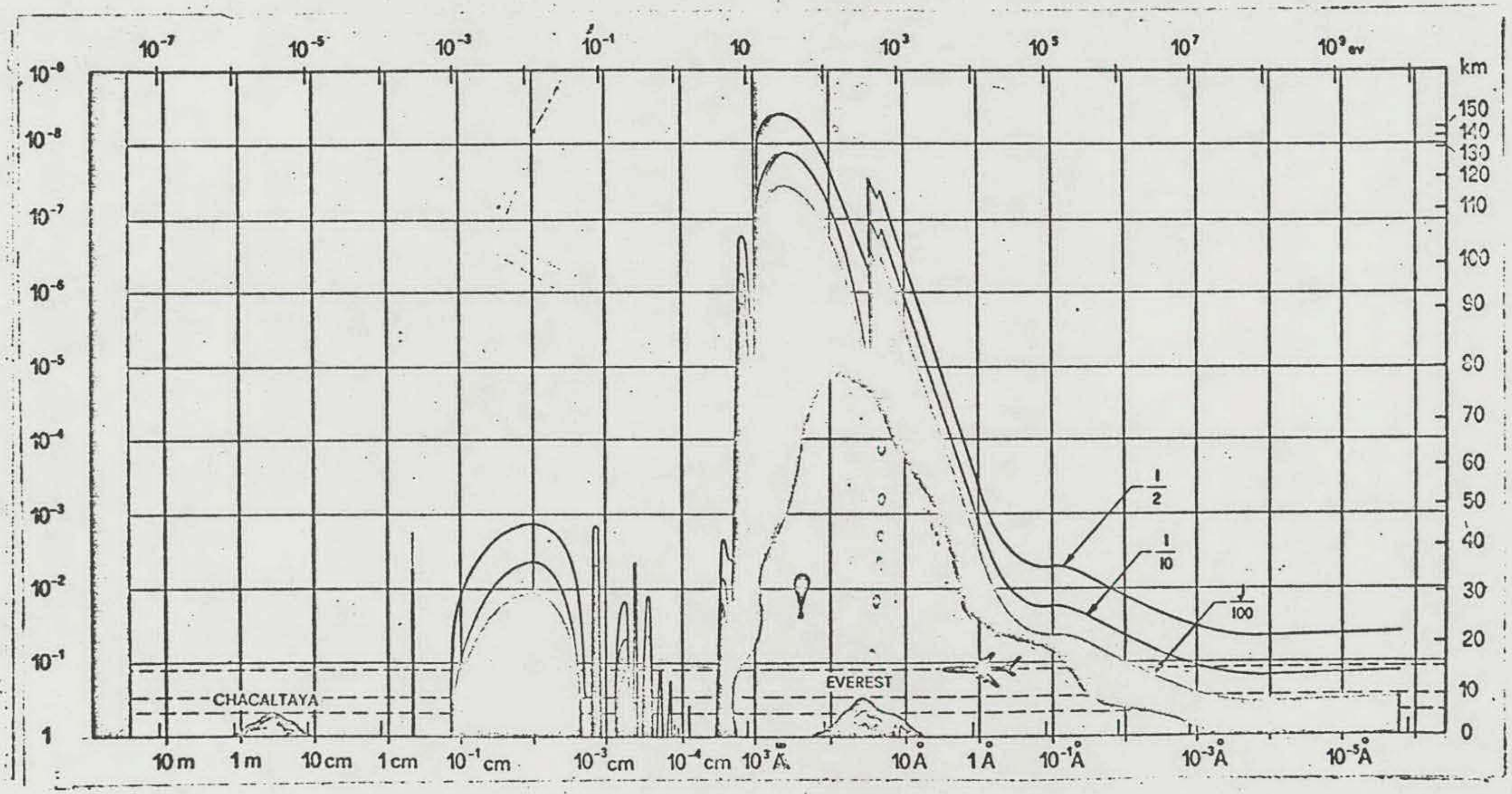

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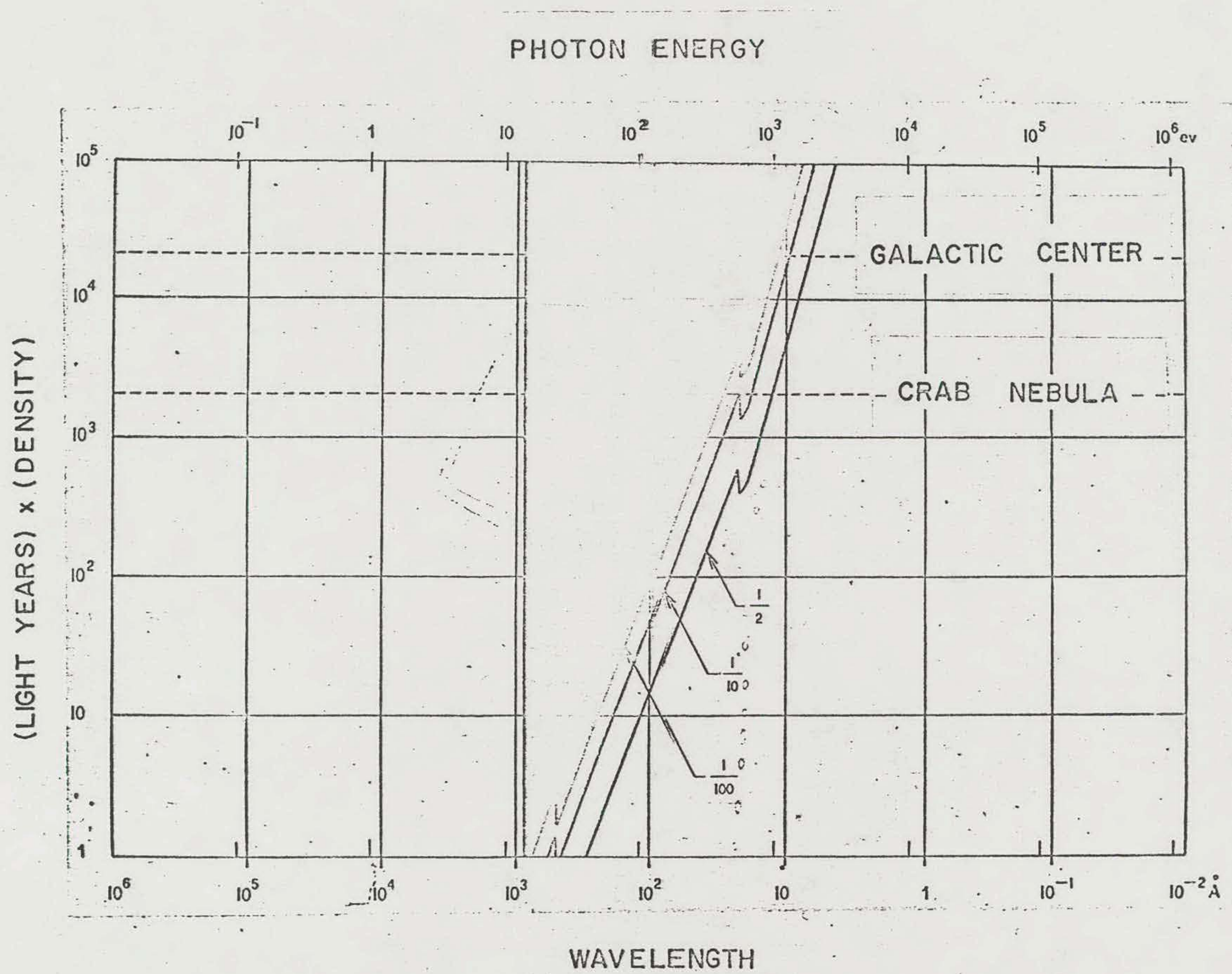

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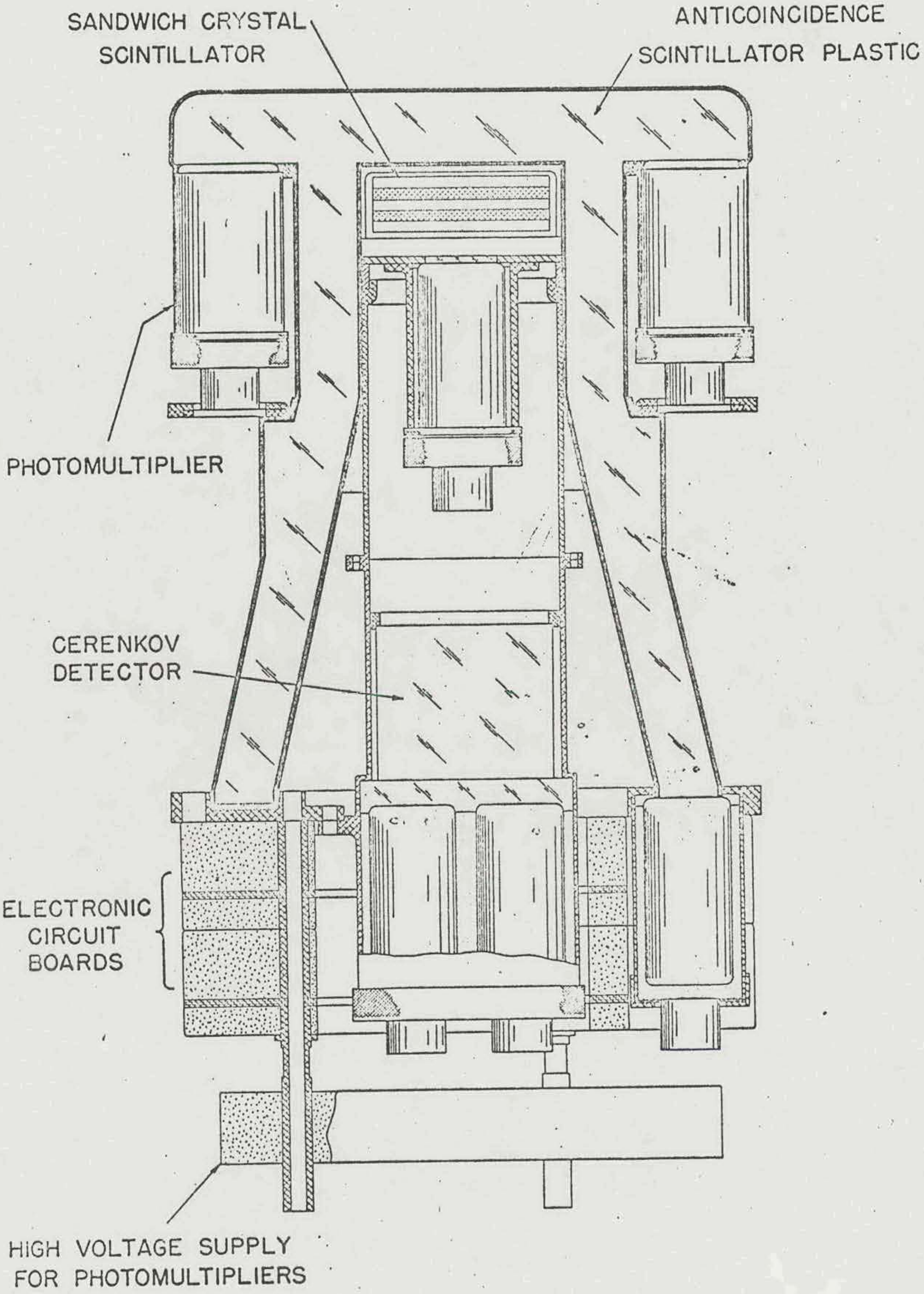
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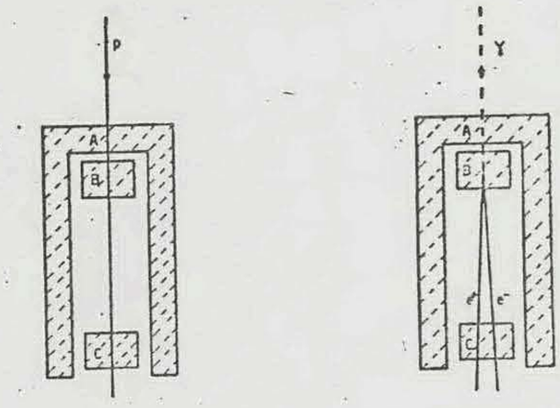
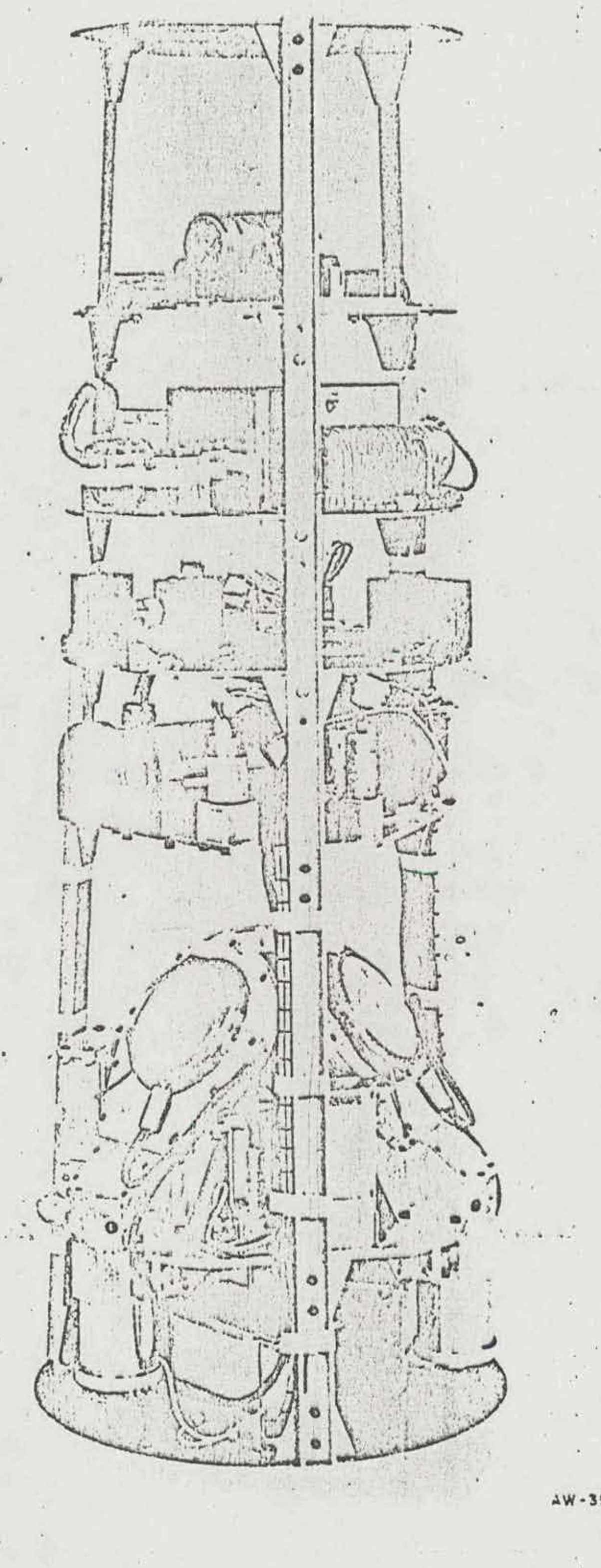


(a) (b)

ROCKET PAYLOAD FOR DETECTION OF X-RAY SOURCES IN THE NIGHT SKY



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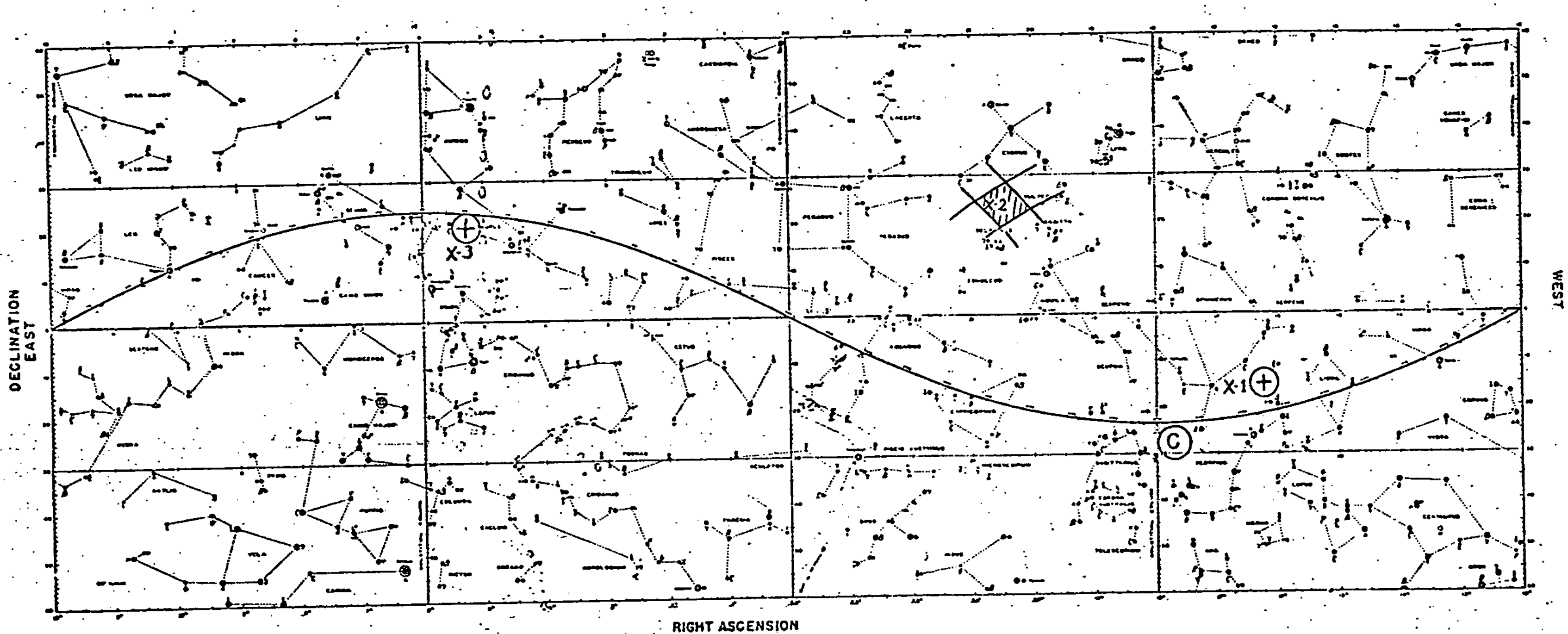
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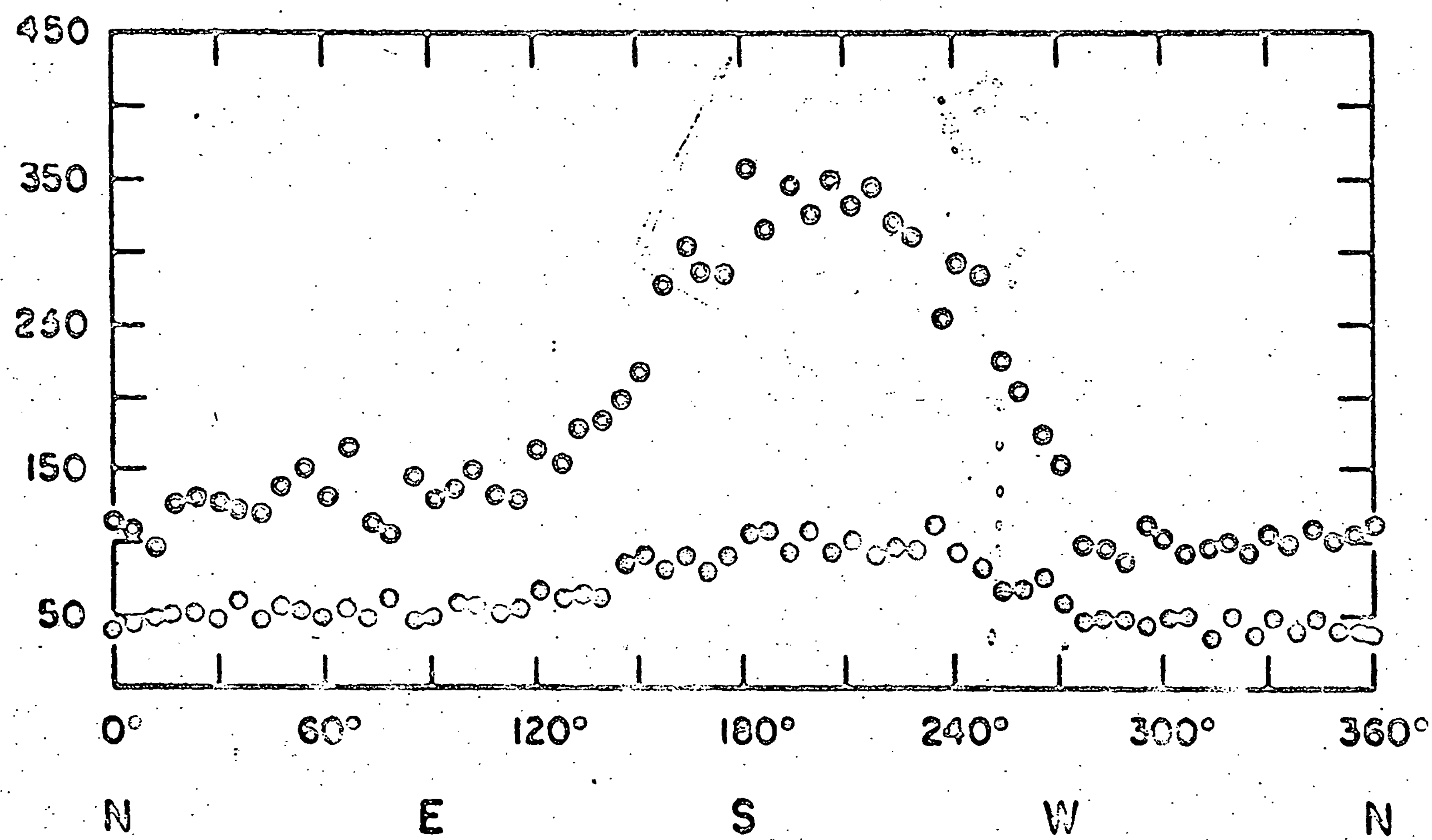

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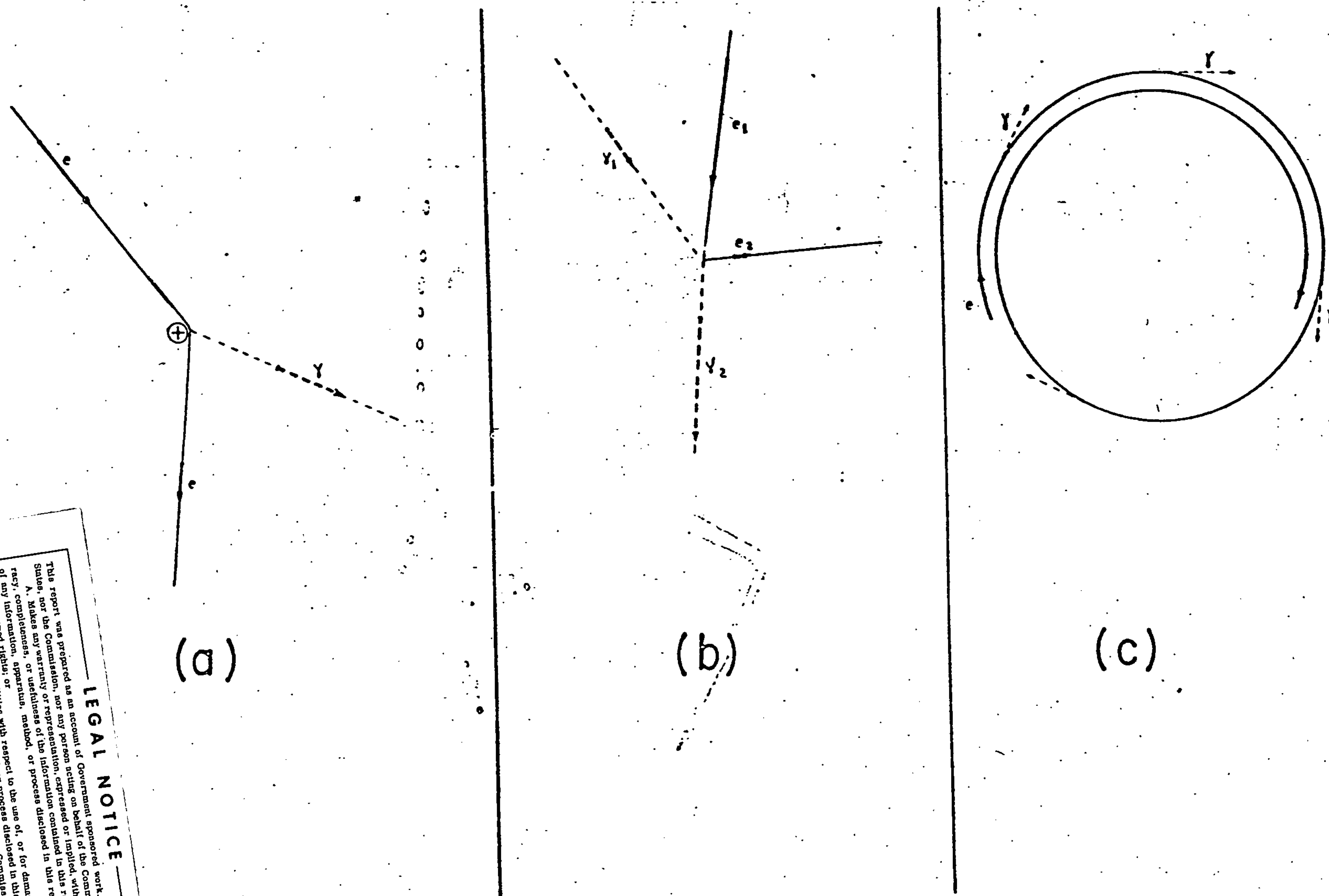
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