OBSERVATIONAL RESULTS OF X-RAY ASTRONOMY

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Résumé. — *Au moyen de compteurs de Geiger montés à bord d'une fusée Aerobee non stabilisée on a identifié dix sources discrètes de rayons X. La distribution de ces sources est aplatie au voisinage du plan galactique. La source Tau XR*-1 *est située à moins de* 1′ *du centre de la nébuleuse du Crabe et son diamètre déterminé par occultation par la Lune est de* 1′. *La position de la source la plus intense Sco XR*-1 *est connue à* 0,5° *près et celle des autres sources à* 1,5° *près environ. Trois de ces sources Sco XR*-1, *Cyg XR*-1 *et Cyg XR*-2 *ne peuvent être associées avec aucun objet optique ou radio connu. Oph XR* 1 *semble coïncider avec la Supernova Kepler* 1604 *et Sgr XR*-1 *est à moins de* 2,3° *de Sgr A. Les cinq sources restantes ne sont pas résolues et leur position n'est pas déterminée assez précisément pour permettre une identification. Ce rayonnement X du Crabe est compatible avec un spectre synchrotron d'indice* — 1,1 *et la valeur du flux de* 1,8 10^{-8} *ergs* cm^{-2} s^{-1} *(*1,5-8 Å*) coïncide avec celle que l'on peut déduire de l'extrapolation du spectre synchrotron optique avec le même indice spectral.*

Abstract. — *Ten discrete sources of X-rays have been identified from observations made with Geiger counters aboard unstabilized Aerobee rockets. The distribution of sources is flattened toward the galactic plane. Tau XR*-1 *is an X-ray source within one arc minute of the center of the Crab Nebula and of angular diameter one arc minute as determined from observation of a lunar occultation. The position of the strongest source, Sco XR*-1, *is known to about* 0.5 *degree and the remaining eight sources to about* 1.5 *degree. Three X-ray sources, Sco XR*-1, *Cyg XR*-1, *and Cyg XR*-2, *are not accompanied by any known optical or radio objects at their positions. Oph XR*-1 *matches the position of the Kepler SN* 1604 *and Sgr XR*-1 *is within* 2.3 *degrees of Sgr A. The remaining five sources are not sufficiently well resolved or positioned to permit identifications with optical or radio sources. The X-ray flux from the Crab Nebula is compatible with synchrotron spectrum with index* — 1.1 *and the flux of* 1.8 × 10^{-8} *erg* cm^{-2} s^{-1} *(*1.5-8 Å*) fits the extrapolated optical synchrotron spectrum with the same index.*

Резюме. — При помощи счетчиков Гейгера, установленных на борту нестабилизированной ракеты Aerobee, были отождествлены десять дискретных источников лучей X. Распределение этих источников сплющено около галактической плоскости. Источник Tau XR-1 расположен менее чем на 1′ от центра туманности Краба и его диаметр, опеределенный затмением Луной, имеет 1′. Положение самого интенсивного источника Sco XR-1 известно с точностью до 0,5°, а других источников приблизительно с точностью до 1,5°. Три из этих источников, Sco XR-1, Cyg XR-1 и Cyg XR-2, не могут быть приписаны ни одному из известных оптических или радиообъектов. Oph. XR-1 по-видимому совпадает со Сверхновой Кеплера 1604 и Sgr XR-1 удалена менее чем на 2,3° от Sgr A. Остальные пять источников не разрешены и их положение не определено достаточно точно, чтобы позволить отождествление. Это излучение X Краба совместимо с синхротронным спектром показателя — 1,1 и значение потока 1,8. 10^{-8} эрг $см^{-2}с^{-1}$ (1,5-8 Å) совпадает с тем, которое можно вывести из экстраполяции синхротронного оптического спектра с тем же спектральным показателем.

EARLY OBSERVATIONS OF X-RAY SOURCES

The first evidence for X-ray emission from the Galaxy was observed by Giacconi, Gursky, Paolini, and Rossi [1] in June 1962. They launched an Aerobee rocket instrumented with Geiger counters sensitive to wavelengths in a band centered at about 3 Å, from the White Sands Missile Range, and detected a strong signal from the general direction of the galactic center. The instrumentation had been designed for an attempt to observe X-rays from the moon and was not equipped with collimation to restrict the field of view narrowly. As a result, the signal was very broad, and accurate definition of the size and position of the source was not possible. A similar experiment was repeated in October 1962 when the galactic center was below the horizon and the strong source was not present. A third attempt, in June 1963, verified the results of the June 1962 flight.

In April 1963, Bowyer, Byram, Chubb and Friedman [2] launched an Aerobee equipped with a counter about 10 times as sensitive as those used by GGPR, and covering a wavelength range 1 to

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(*) The paper presented at Liège by H. Friedman as been supplemented by results of an additional rocket survey in November 1964.

(**) Sponsored jointly by the Office of Naval Research and the National Science Foundation.

8 Å. In front of the counter was a hexagonal honeycomb structure which provided collimation. The field of view was limited to about 10 degrees at half maximum of the transmission pattern. The rocket was deliberately given a slow spin to make it precess with a large cone angle. As a result, the circle of sky which was swept out by each roll slowly turned through the sky. Almost all of the celestial sphere above the horizon was thus scanned during the flight. At the time, the galactic center was below the horizon, but about 58 % of the celestial sphere was observed (Fig. 1). In this large expanse of sky, the detector found one outstanding source in Scorpius and another, about one-eighth as intense, in the direction of the Crab Nebula. No other discrete sources could be identified above the general background.

The counter was of the proportional type with an effective window area of 65 cm^2 of beryllium, 0.005 inch thick. Pulse height discrimination was used to give rough spectral information by sorting into three channels : 1 to 1.5 Å, 1.5 to 2.5 Å, and 2.5 to 8 Å. From the observed distribution it appeared that the Scorpius source could be fitted to a 2 × 10^7 °K. black body curve.

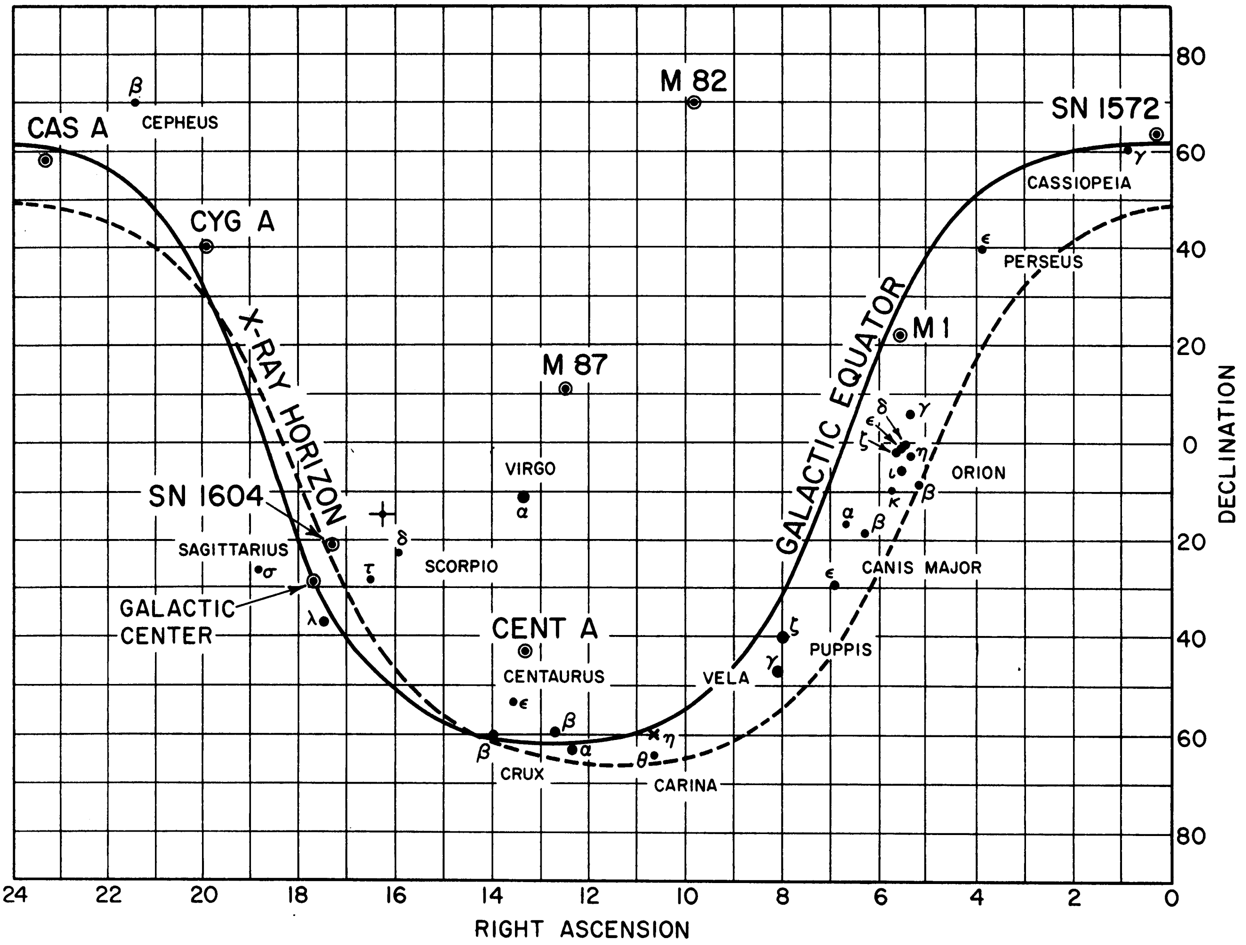

Fig. 1. — X-ray horizon from peak altitude of Aerobee rocket launched April 29, 1963, at the White Sands Missile Range. All of the celestial sphere above horizon was scanned during the course of the flight. Positive X-ray responses were received from one source in Scorpio and from M 1. No detectable signal was observed in scans of Cas A, Cyg A, Cent A, M 87, M 82, and SN 1572.

The source in Scorpius was clearly detected on eight separate scans. Figure 2 shows the direction of each scan with intensity in counts per 0.09 second indicated along each path. The circles approximate equal intensity contours at counting rate levels of 300, 200 and 100 per second, and indicate a peak intensity of about 400 counts per second at 16 h 15 m right ascension and — 15° declination. Since the Scorpius source was scanned 8 times in the 1963 flight, sufficient data were available to locate the position of peak intensity with rather high accuracy. The distribution of observed counting rates versus angular displace-

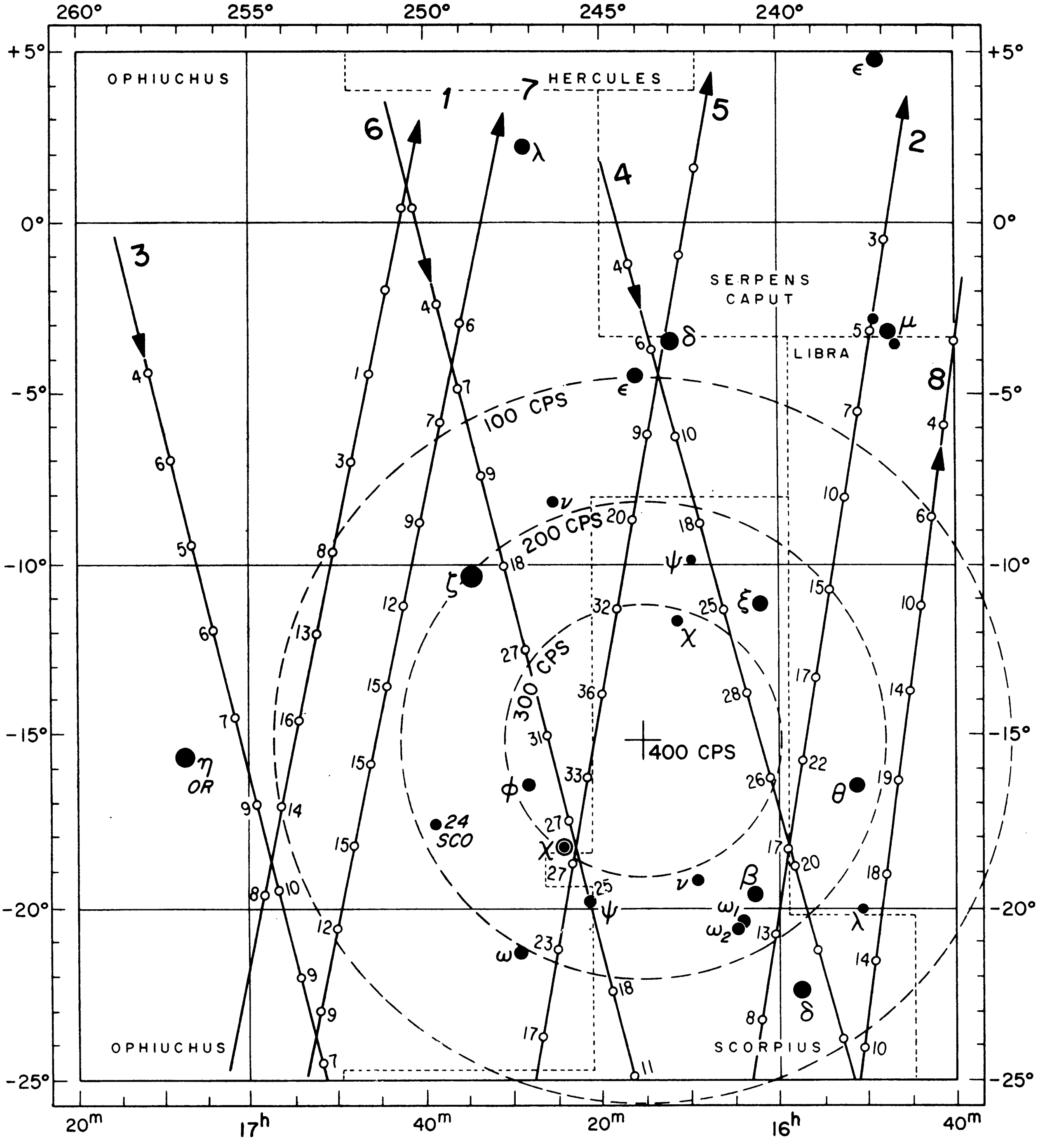

Fig. 2. — Tracks of eight scans across Scorpius region. Numbers along tracks are counts per 0.09 s interval. The dashed circles are best fits to equal intensity contours and indicate a central intensity peak of 400 c.p.s. at α = 16 h 15 m, δ = — 15° (Ref. 3).

ment from the peak intensity is shown by the dots in Figure 3. The displacement of the average of the measured pattern from the computed collimator transmission curve for a point source is — 0.2°. We conclude that the true size of the Scorpius source is probably less than 0.2°.

The Crab Nebula was included in the field of view of the detector on three scans, one of which passed directly over the source, the second 1.5° off, and the third 2.5° off (Fig. 4). By averaging these three scans, we obtained a signal from the source almost 5 times the standard deviation of the

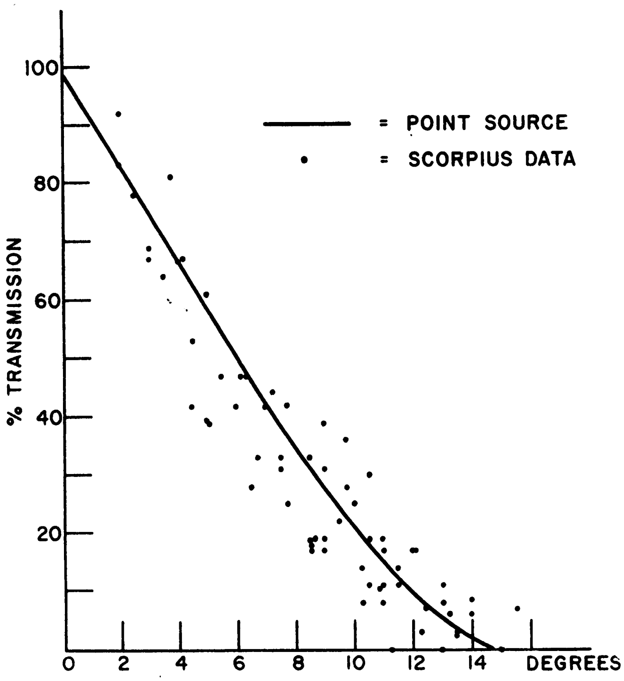

FIG. 3. — Solid line is theoretical transmission curve of honeycomb collimator used in April 1963 Aerobee flight. The dots show the angular dependence of observed counting rates, with peak signal normalized to 100 % transmission. Average displacement from transmission curve is — 0.2°.

background. The direction of the peak response coincided with the Crab Nebula within 2°, which was as close as the statistical accuracy of the scanned profile permitted the positioning.

The intensity of X-rays from the Scorpius source is comparable to that emitted by the quiet Sun in the same wavelength range, yet the immediate neighborhood of the source is devoid of any visibly bright star, nebulosity, or radio emission. The Crab Nebula, in contrast, is a conspicuous source of radiation over a range of wavelengths from radio to visible. Its visible and radio Nebula is about 6 light-years across and expanding at about 1000 km per second. The Nebula is the debris of a supernova explosion that occurred in 1054 A. D., but no remnant of the original star can be identified.

On the basis of these early observations, it was proposed that both X-ray sources could be neutron stars, the highly compressed cores that may remain after explosion of the outer portions of supernovae. According to the theory of a neutron star [3, 4] one can predict a strong X-ray source with essentially no visible or radio emission, such as required to explain the Scorpius source. A neutron star might also exist unobservable except for its X-ray emission in the center of the Crab Nebula.

LUNAR OCCULTATION OBSERVATION OF THE CRAB NEBULA

Present rocket X-ray techniques are too primitive to permit definition of the sizes of these sources with sufficient resolution to support a stellar hypothesis. We were able, however, to resort to the method of lunar occultation, and on 7 July 1964, at 2242 : 30 U. T. an Aerobee rocket was launched from White Sands Missile Range to observe the occultation of X-ray emission from the Crab Nebula. Lunar eclipses of the Crab Nebula are grouped at intervals of approximately 9 years. The eclipse of 7 July covered the Nebula at the rate of one-half minute of arc per minute of time. Since the Nebula measures 6 minutes across its greatest dimension, to observe a full eclipse would require 12 minutes of X-ray measurements from a rocket above the atmosphere. But the Aerobee rocket affords only 5 minutes of time above 100 kilometers. The interval for the experiment was therefore chosen so that the eclipse of a central portion of the Nebula over a range of about 2 minutes of arc would be observed. The rocket was equipped with a stabilization system to orient two X-ray telescopes toward the Crab and to maintain steady pointing during the course of the occultation. If a neutron star X-ray source existed in the center of the Crab, the occultation would be expected to produce an abrupt disappearance of X-rays. A gradual disappearance of X-ray emission would indicate that the X-ray source was an extended cloud.

Two Geiger counters of nearly identical construction were used to detect the X-rays. Each counter was in the form of a shallow rectangular box strung with five anode wires. Across the face of the box was a plastic window of Mylar, making an X-ray transmitting window of 114 cm^2 area. To provide crude wavelength discrimination, one window was 0.001 inch thick ; the other was 0.00025 inch thick. Both counter volumes were connected by tubing so that they shared a common gas filling of 89.5 % Ne, 9.5 % He, and 1 % isobutane at atmospheric pressure. A gas flow system was used to permit flushing both tubes in series, just prior to launch, from a storage tank of gas carried in the rocket. During flight, the gas content was static at a regulated pressure. Figure 5 illustrates the calculated spectral efficiencies of the two counters. Up to a wavelength of about 3 Å both

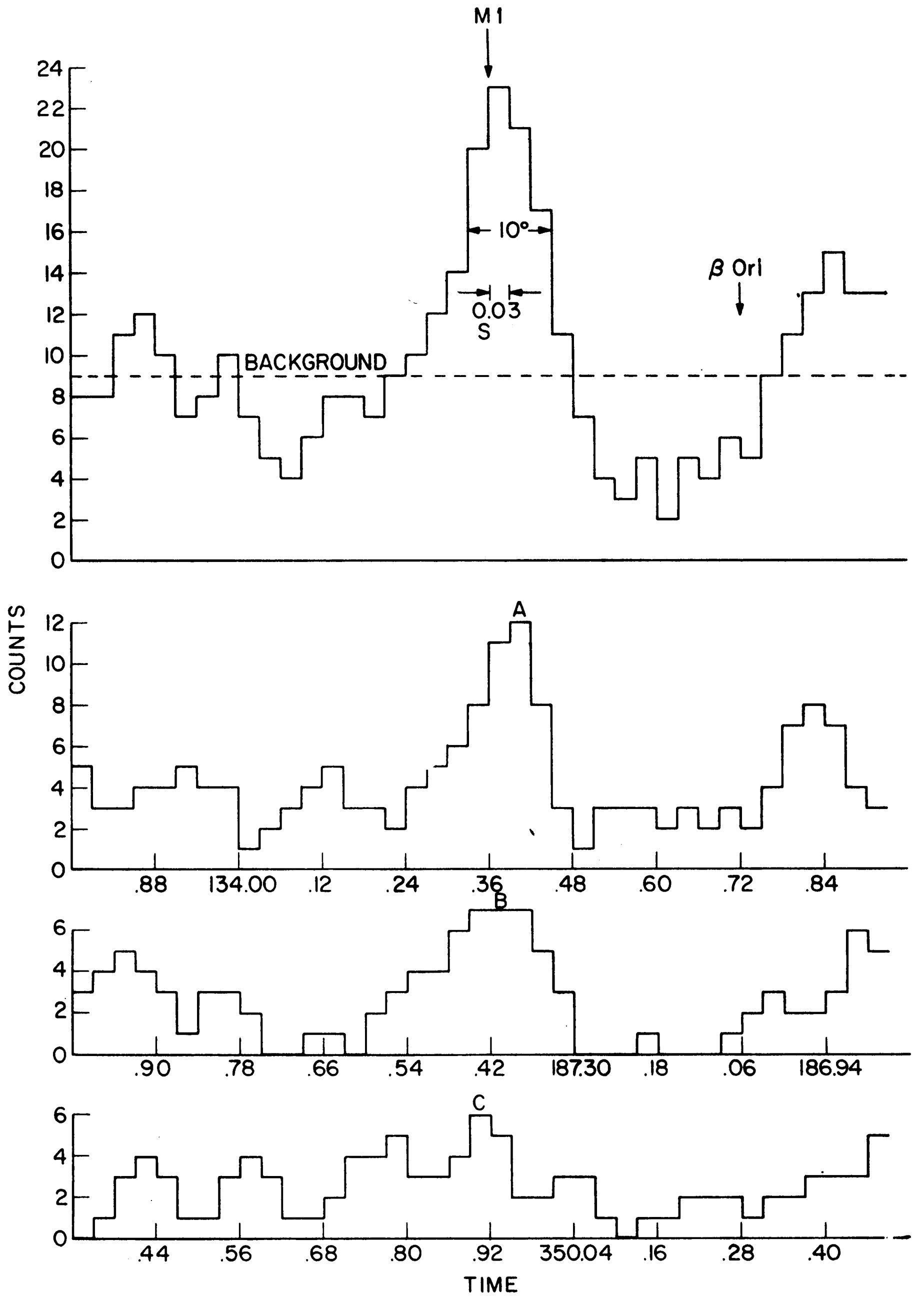

Fig. 4. — Observation of the X-ray flux from the Crab Nebula on 29 April 1963. The upper graph is the sum of three separate scans A, B, and C. In scan A, the source passed directly across the center of the field of view, which was 10° in diameter; scan B was 1.5°, and scan C was 2.5° off center. A running mean of counts per 0.09 second is plotted at intervals of 0.03 second. The peak intensity corresponds to 52 count per second.

tubes had almost identical responses, but at longer wavelengths the thinner window provided increasingly greater efficiency. The two counters were mounted, one above the other, with their windows in the same plane facing outward, in a direction normal to the long axis of the rocket. Each window was covered by a honeycomb collimator, which limited the field of view. The angular response was roughly bell-shaped with a maximum cutoff angle of 14° on either side of the normal direction.

The Aerobee was stabilized by a cold gas jet-gyro referenced control system, manufactured by the Space General Corporation under contract to the U. S. National Aeronautics and Space Administration. From analysis of the Sun signal, magne-

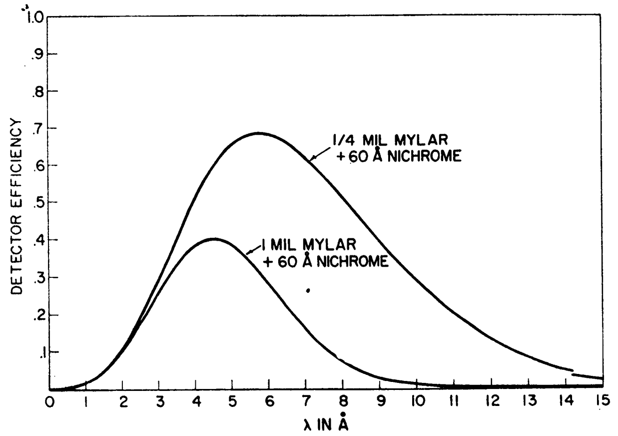

Fig. 5. — Computed spectral sensitivity curves for Mylar window counters.

tometer signals, and the gyroscope data, we conclude that the rocket fixed on its final orientation at 160 seconds after launch and that the detectors pointed within 4° of the Crab. From 160 to 400 seconds, the pointing did not deviate by more than one-fourth degree.

Figure 6 shows the variation of X-ray counting rate through the course of the flight. At 100 seconds the rocket was above the absorbing atmosphere for X-rays of wavelengths shorter than 10 Å. As it rolled to acquire the Crab, the detectors scanned the Sun. The responses of the counters to the entry of the Sun into the field of view were almost perfectly mirrored as the Sun passed out of the field of view. There was no indication of counting hysteresis and, in fact, test exposures to intense sources in the laboratory had revealed no tendency of the counters to lag in recovery. Thirteen seconds elapsed between disappearance of the Sun's signal and acquisition of the final orientation to the Crab.

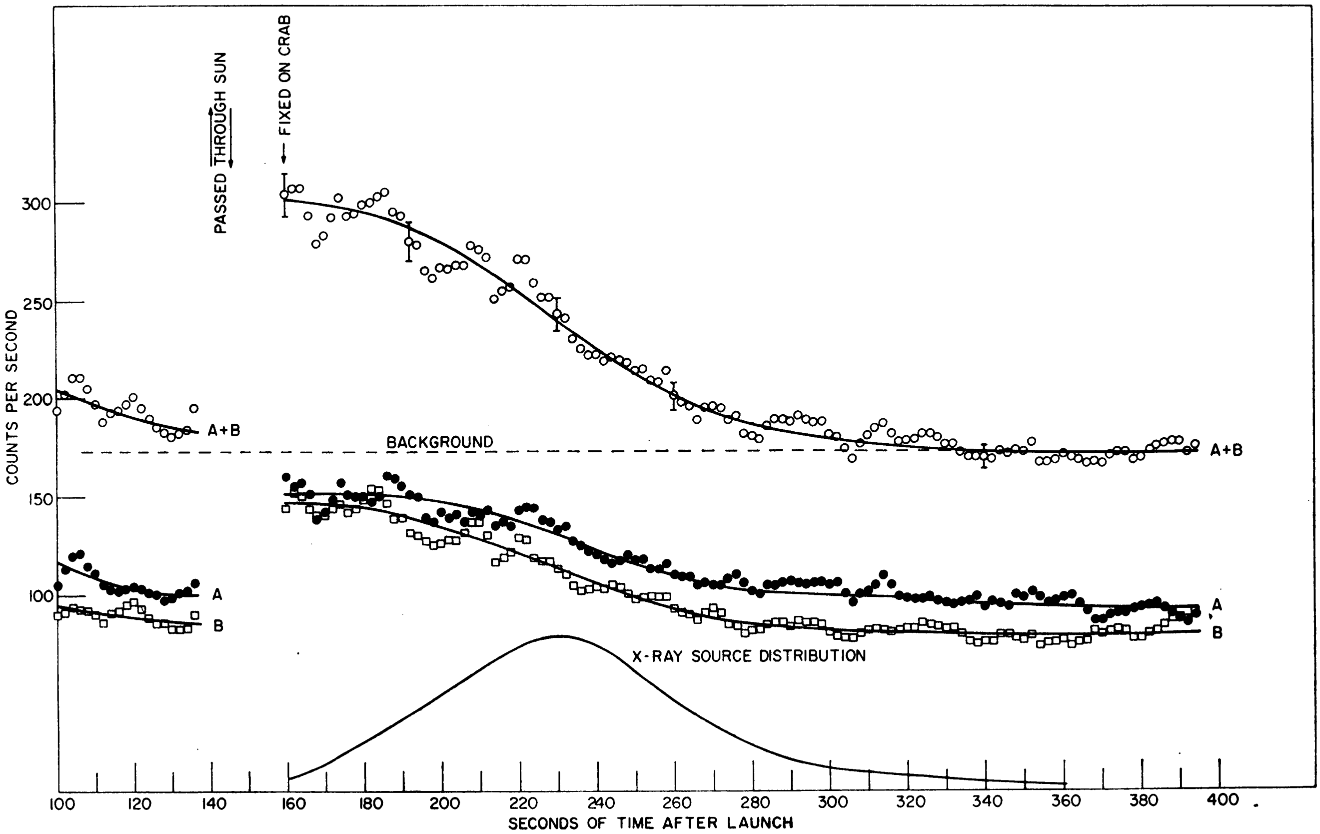

Fig. 6. — Variation of the observed X-ray flux during the course of flight of July 7, 1964. The Mylar windows of counters A and B were 1 mil and 1/4-mil thick, respectively. Counting rates were computed from the time required for a fixed count of 768 in each counter. A running mean is plotted at 2-second intervals. The X-ray source distribution is the derivative of the A plus B curve.

From 160 to 400 seconds, the variation in X-ray counting rate can be attributed to the progress of the lunar occultation. Figure 7 shows the relationship between the time after launch and the disappearance of the Crab behind the Moon. The peak of the flight was 221.4 km, which was reached at 250 seconds. For all of the time interval from

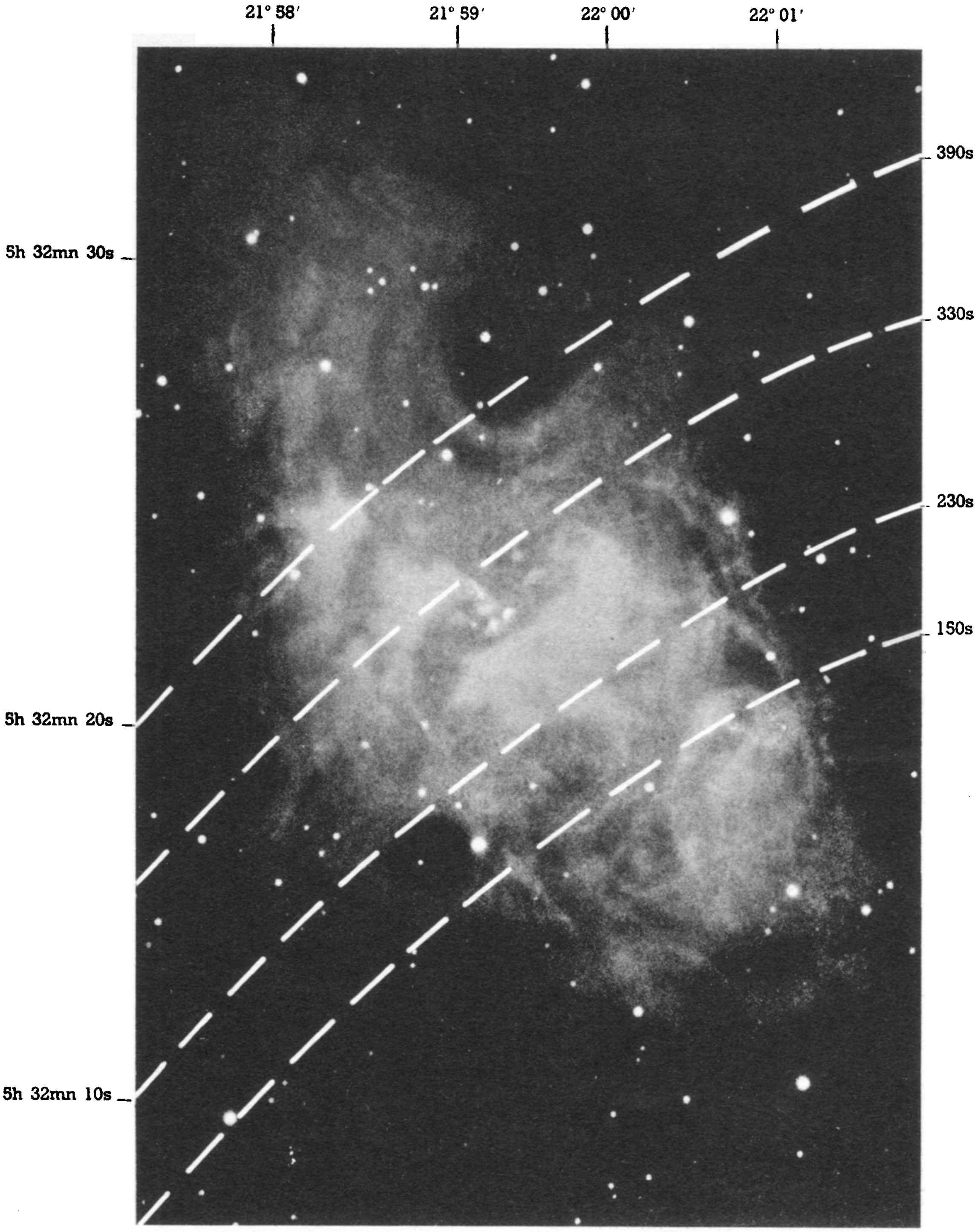

Fig. 7 : **Progress of the occultation** of the Crab Nebula measured in seconds of time after launch of the rocket from White Sands Missile Range. The dashed curves represent the positions of the edge of the moon. A maximum rate of decrease in X-ray flux was observed at about 230 seconds.

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160 seconds (184 km) to 320 seconds (199 km) during which the decrease of X-ray flux was observed, the rocket was more than five scale heights above the level of unit optical depth of the atmosphere for wavelengths shorter than 10 Å (the limit of counter A with its 1-mil Mylar window) and more than three scale heights above unit optical depth for 60 Å (the limit of counter B with its 1/4-mil Mylar window). The decrease of X-ray flux during the occultation was, therefore, not related to the variation of rocket altitude.

At the beginning of the occultation, each counter exhibited a rather flat trend of counting rate versus time. This was followed by a relatively rapid decline to the background rate which had been observed in the 100 to 130 second interval. The curve of the sum of the two counter responses was differentiated to give the source distribution of Figure 6. The results indicate that the total angular width of the source is about 1 arc minute, which corresponds to about one light-year at a distance of 1100 parsecs. The maximum of the X-ray flux distribution was observed at about 230 seconds, when the occultation had not quite reached the center of the visible Nebula. The fact that both counters responded with nearly the same counting rates would seem to indicate that the X-ray flux must be confined primarily to the region below 5 Å. However, a subsequent observation of the Crab has shown that the long wavelength sensitivity of counter B had deteriorated before launch. The detectors had been exposed to rain while the rocket was in the launching tower for an hour before launch. Mylar is very pervious to water vapor, which destroys the long wavelength sensitivity of the counter. Apparently the flushing of the counters before launch was not adequate to remove the trace of water vapor contaminant.

X-RAY SURVEYS, 1964

Continuing the search for discrete X-ray sources, we conducted two additional Aerobee surveys in 1964 from the White Sands Missile Range in New Mexico. The first of these was launched on June 16 when the zenith coordinates were 19 h and 30 minutes right ascension, declination 32.4°. The galactic plane was mapped from the southern region of Scorpius, through Cygnus, to the northern part of Perseus. For the second flight, on 25 November, the zenith right ascension was 8 h and 48 minutes, and the survey extended through Taurus to the southern portion of Puppis.

The Geiger counters were sensitive to wavelengths from 1 to 15 Å and were similar to those described in connection with the occultation observation, but of larger area. Some of the counters were equipped with 1/4-mil Mylar windows and some with 1/2-mil Mylar windows. With the honeycomb collimator in place, the effective window aperture of each counter was 453 cm². By pairing two counters, mounted in the same plane parallel to the length of the rocket, an effective area for X-ray detection of about 906 cm² was obtained. This was about 14 times as great as the window area used in the April 1963 survey. Two sets of paired counters were used in each rocket and were oriented 180° apart. Because of the large area of plastic film window, a gas flow system was required. The mixture of 89 % neon, 10 % helium, and 1 % isobutane was maintained at atmospheric pressure.

The counting rates of the individual counters, as well as the summed pairs, were metered by separate rate meter circuits. In the November 1964 flight, the cosmic ray background of one pair of counters was reduced by an anticoincidence arrangement which utilized a third pair of tray counters, with thick windows, mounted back-to-back with the X-ray survey counters.

On June 16, the rocket reached a peak altitude of 127 km and rolled with a period of about 8.5 seconds. Its precession period was 422 seconds and the precession cone angle was 144°. A solution of the orientation history was obtained to an estimated accuracy of 1.5°. The November 25 flight reached an altitude of 200 km. The roll period was 6.35 seconds, precession period 236 seconds, and cone angle about 140°.

In the June 1964 survey, satisfactory data were obtained from only one pair of counters, which swept across most of the accessible sky. Much of the survey showed only a statistically varying cosmic ray background with little difference between signals observed looking up and down. Superposed on this background were several X-ray signal peaks. The thin lines that lace the map of Figure 8 are the traces of the counter view vector as it swept across the celestial sphere. Where the counters responded above background, the scan lines of Figure 8 are covered by shaded strips. All of the observed X-ray sources are located relatively near the galactic plane. Those on scans 3, 4, 5, 6 and 7 are within 5° of the galactic equator, and those on scans 1 and 10 are at galactic latitudes of 11° and 22°, respectively.

The isolated responses on scans 9 and 10 fit the

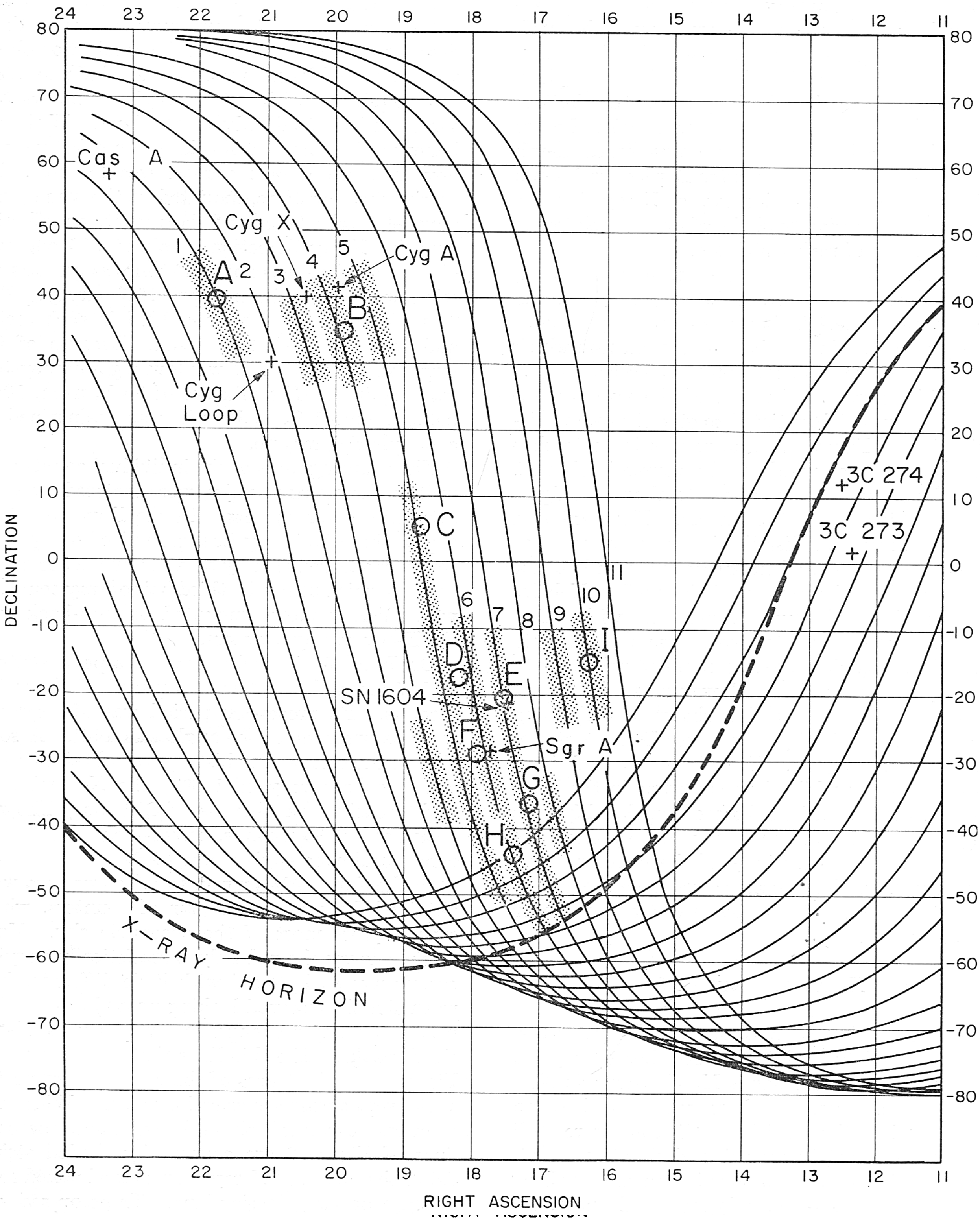

FIG. 8. — **Map of sky scanned by X-ray detectors in June 16, 1964, Aerobee flight. Thin lines trace path of view vector across celestial sphere on successive rolls. Shaded segments indicate portions of scan in which clearly detectable X-ray signals were observed above background. Circles are positions at which discrete sources have been identified.**

position of the Scorpius source, which we derived from the April 1963 observation. It remains the strongest source thus far observed. The telemetry record of scan 4 through Cygnus, which shows the second strongest source, is reproduced in Figure 9.

The strong Scorpius source was observed late in the flight on passes 9 and 10 when the rocket was re-entering the absorbing atmosphere at 100.0 km and 93.4 km. On pass 11, when the rocket was at 86.7 km, no signal was detected. These three observations permit us to deduce roughly the spectral composition and the total flux out to about 10 Å. The pass at 93.4 km scanned directly across the previously determined position of the source. On the preceding and following passes, the displacement of the source relative to the center of the field of view was about 6.5°, so that the collimator transmission was about 25 %. The filtering effect of the air above the rocket permits us to infer qualitatively the spectral composition. At 93.4 km, with the Scorpius source at an elevation of 22.5°, unit optical thickness of the overhead air mass corresponded to $\lambda = 6$ Å. The observed flux of 6.6 counts per $cm^2.s$ was, therefore, confined largely to the range 1 to 6 Å. On the preceding pass at 100 km, the counting rate was 4.6 counts per $cm^2.s$. When corrected for the collimator transmission factor of 25 %, the flux becomes 18.7 counts per $cm^2.s$. The difference in flux measured at the two altitudes may be attributed principally to radiation of wavelengths longer than 6 Å. Unit optical thickness corresponded to 8 Å at 100 km and the spectrum was effectively cut off at about 10 Å. At 86.7 km, the wavelength for unit optical thickness was 4 Å. The combination of atmospheric opacity and reduced collimator transmission made the source undetectable against the background on scan 11, Figure 8. We conclude that approximately one-third of the observed flux from the Scorpius source falls below 6 Å and two-thirds between 6 and 10 Å. If the X-ray emission is attributed to the black body radiation of a neutron star, the temperature of the Scorpius source, based on this spectral evidence, would be in the neighborhood of 2 or 3 million degrees.

Three of the X-ray signals, labeled A, B, and I on the map of Figure 8, appear to come from clearly isolated discrete objects. Signal I fits the position which we identified with the strong Scorpius source in 1963. Signal B was seen on three successive passes through the Cygnus region. The telemetry record of Scan 4, when the source passed close to the center of the field of view, is reproduced in Figure 9. The signal envelope is consistent with the expected angular response from a source of small angular width compared to the collimator aperture. Although Cygnus A, the brightest extragalactic radio source in the sky, was within 6° of position B, there is no evidence of any X-ray contribution from it. Signal A was also discrete and there is no outstanding optical or radio object at its position.

The portions of Scans 5, 6 and 7 which cover the general region near the center of the Galaxy reveal a complex of emission which can be best resolved as the sum of six " point " sources labeled C, D, E, F, G and H. Table I lists the positions of the nine sources identified by the survey, the observed counting rates, and the fluxes computed for two assumed black body spectra. All of the listed sources were observed as signals clearly above background on each of two counters. Also included in Table I is the Crab Nebula. The sources are labelled " XR " for X-ray, and numbered within the various constellations according to brightness.

In the survey of 25 November, satisfactory data were obtained from three of the four X-ray counters. Despite the wide expanse of sky that was searched from Perseus to Puppis, the only source observed was the Crab Nebula. The flux was 2.7 counts per square centimeter per second through 1/4-mil Mylar and 1.6 counts per square centimeter per second through 1/2-mil Mylar.

Discussion

The surveys completed thus far cover about 70 % of the celestial sphere. All of the X-ray sources observed lie rather close to the galactic plane and within plus and minus 90° of the galactic center. This distribution resembles that of galactic novae and suggests that all of the X-ray sources thus far observed may be associated with supernova remnants in the Galaxy. Tau XR-1 was located by the lunar occultation observation of July 7, 1964, within 1 arc minute of the center of the Crab Nebula. Oph XR-1 fits the position of the 1604 Kepler supernova within the 1.5° accuracy of the observation.

There appear to be at least two types of X-ray " stars ", those associated with radio and visible sources, such as Tau XR-1, Oph XR-1, and possibly Sgr XR-2, and those like Sco XR-1, Cyg XR-1, and Cyg XR-2, which are not identified with radio or optical sources at their positions. Al-

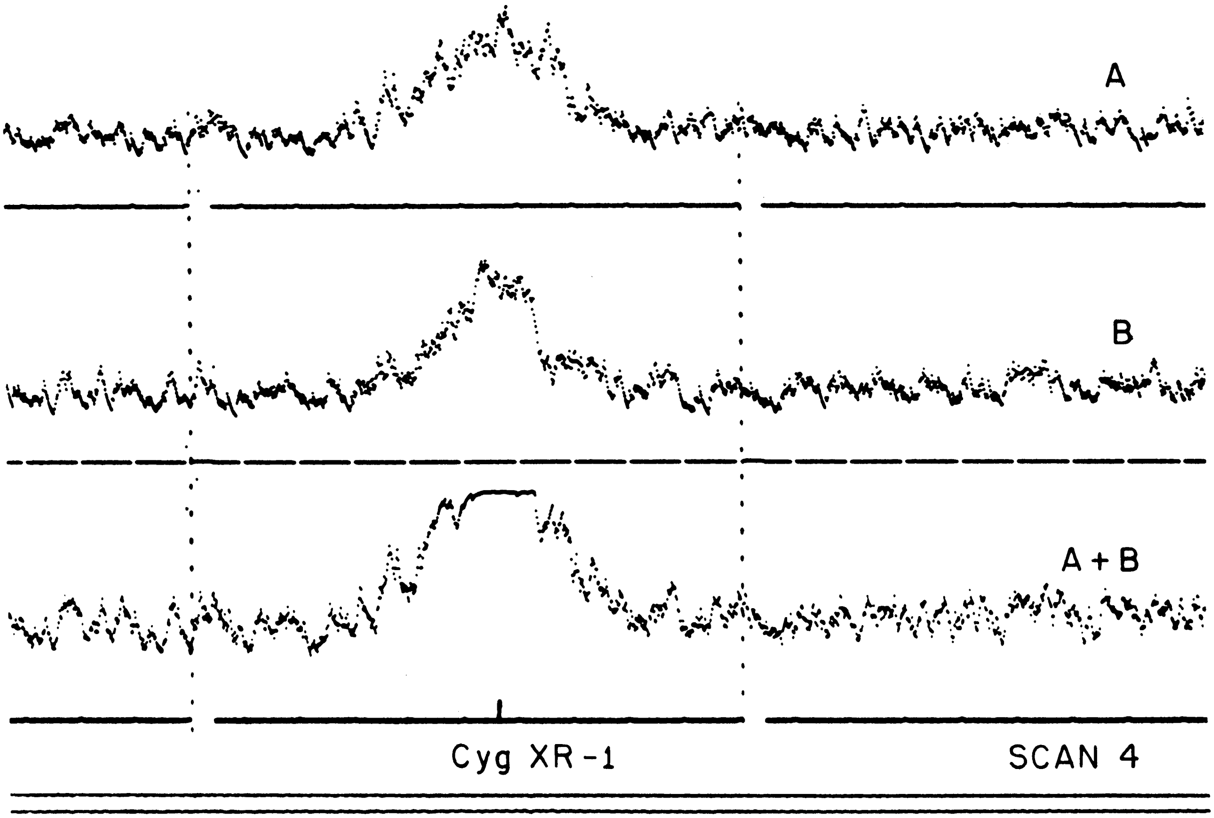

FIG. 9. — Telemetry traces of Cyg XR-1 signals. Traces A and B are from individual counters, each equipped with 1/4-mm Mylar window. Trace A + B is sum of signals from A and B. Dotted vertical lines are spaced one second apart. Full deflection corresponds to 2000 c.p.s.

TABLE I

X-RAY SOURCES

SOURCE	R. A. (1950)	DEC.	FLUX (a) (counts/cm^2.s)	10^{-8} erg/cm^2.s (b)	(c)	REMARKS
—	—		—	—		—
Tau XR-1	$05^h31.5^m$	— 22.0°	2.7	5.5	1.1	Within 1′ of optical center of nebula
Sco XR-1	16^h15^m	— 15.2°	18.7	38.0	7.9	Previous measurement Ref. (2) 12 × 10^{-8} erg/cm^2.s (b)
Sco XR-2	$17^h\ 8^m$	— 36.4°	1.4	2.9	0.6	
Sco XR-3	17^h23^m	— 44.3°	1.1	2.3	0.5	
Oph XR-1	17^h32^m	— 20.7°	1.3	2.7	0.6	1.1° from SN 1604
Sgr XR-1	17^h55^m	— 29.2°	1.6	3.3	0.7	2.7° from galactic center
Sgr XR-2	18^h10^m	— 17.1°	1.5	3.0	0.6	2° from M 17
Ser XR-1	18^h45^m	5.3°	0.7	1.5	0.3	
Cyg XR-1	19^h53^m	34.6°	3.6	7.3	1.5	
Cyg XR-2	21^h43^m	38.8°	0.8	1.7	0.4	

(*a*) Uncorrected for atmospheric absorption. Measured 1/4-mm Mylar window.
(*b*) Computed for 2 × 10^7 °K black body, 1.5- 8 Å.
(*c*) Computed for 5 × 10^6 °K black body, 1.5- 8 Å.

though the occultation observation of Tau XR-1 showed that its diameter was about one light-year, little is known of the dimensions of the remaining X-ray stars, other than that the true size of Sco XR-1 is probably less than 0.2°.

Since both the radio spectrum and optical emissions from the amorphous mass of the Crab have been identified as synchrotron radiation, can the observation of X-ray emission from an extended source also be attributed to synchrotron radiation ? **Woltjer** [5] has estimated the synchrotron flux in the far ultraviolet by assuming it to be the source of excitation of the filamentary shell. A simple extrapolation of the short wavelength end of the optical spectrum through **Woltjer**'s ultraviolet estimate to the X-ray region falls within an order of magnitude of the observed X-ray flux. **Shklovsky** [6] has also pointed out that with a slight modification in the value of the interstellar absorption of light from the Crab Nebula it is possible to fit the optical observations of synchrotron emission to the X-ray flux at about 3 Å with a common spectral index of — 1.2. The spectral evidence derived from the 25 November flight can be fitted to a bremsstrahlung spectrum at about 10^7 °K, a black body at about 5×10^6 °K, and a synchrotron spectrum with an index of — 1.1. More precise spectral data are urgently needed, but the evidence seems to favor the synchrotron process.

The Crab Nebula appears much larger at meter wavelengths than in the visible range. Most of the optical emission is concentrated within a region measuring about two minutes of arc in diameter, about 2 to 3 times smaller than the radio size. The diameter of the X-ray emitting volume is less than half that of the optical. **Shklovsky** [6] suggests that the small size of the X-ray nebula may be related to the lifetimes of highly relativistic electrons responsible for generation of X-ray synchrotron radiation. The lifetime varies inversely with the 3/2 power of the magnetic field multiplied by the square root of the frequency. Estimates of the field strength range from 10^{-4} to 10^{-3} gauss, and it is most likely that the higher figure is reached near the center of the nebula. An electron radiating in the X-ray spectrum, $\sim 10^{18}$ cycles per second, in a field of 10^{-3} gauss would have a half-life of about 0.8 years. **Shklovsky** proposes that these high energy electrons, $E \sim 10^{13}$ eV, are accelerated in a small central region of the nebula. Traveling at nearly the speed of light, they could get no farther than about one light-year from the region of acceleration. This would limit the size of the X-ray emitting region to roughly the observed value.

Shklovsky [7] and **Oda** [8] have called attention to the close coincidence between the position which we established for the Scorpius X-ray source and the position proposed by **Hanbury-Brown**, **Davies**, and **Hazard** [9] for the center of a radio emitting shell associated with the radio object referred to as " The Spur ". Radio frequency isophotes at 38 megacycles per second and 158 megacycles per second have shown a spur of relatively intense emission which emerges from the galactic plane near the Sun and curves about an apparent center at 15 hrs, — 20°, Considering the approximate nature of this position fix (about 10°), it agrees quite well with the position of 16 hrs and 15 minutes, — 15° for the X-ray source in Scorpius. **Hanbury-Brown**, *et al*, proposed that The Spur may be an object similar to the Cygnus loop which is believed to be the remnant of a Type II supernova. The Cygnus loop emission has a distribution consistent with a shell source about 10 pc thick and 40 pc in diameter at a distance of 770 pc. By analogy, The Spur would be at a distance of about 50 pc, and **Shklovsky** suggests that the age of this near supernova may be 50,000 to 100,000 years. If the intensity of X-ray emission is simply related to the age, the Scorpius source may be 100 times less intense than the Crab, but its close proximity would still make it appear brighter. However, any visible nebula of synchrotron radiation associated with it would have too low a surface brightness to be detectable against the background sky. The same would be true of its radio synchrotron emission. Assuming that the Scorpius supernova remnant contains an X-ray emitting region about one light-year in diameter, its angular width at 50 pc would be about one-third degree. The scan data of the April 1963 flight indicated only that the diameter did not exceed 0.2°. However, it should be possible in future observations with narrower mechanical collimation to establish the dimensions to a minute of arc or better.

If Oph XR-1 is truly associated with SN 1604, it may be meaningful to compare it with Tau XR-1, since both are presumably Type I supernovae. Recent distance estimates place the Crab at 1.5 kpc and the Kepler supernova perhaps as far as 9 kpc. Distance alone should make the Crab approximately 50 times as bright, but its X-ray flux is only twice as bright. The Crab, however, is 550 years older, and the weakness of its X-ray flux may be attributed to aging at the rate of about 5 % per year. If the Kepler supernova is only 4 kpc distant, the rate would be only 1 % per year.]

In view of the theoretical predictions of X-ray emission from the region of the galactic center [10, 11] it is interesting to note that Sgr XR-1 is indeed close to the direction of the galactic center. We have located the X-ray source about 2.7° from Sgr A. The displacement appears to exceed the estimated positional uncertainty, but the difference is not so great as to rule out positively the possibility of a coincidence between the X-ray and radio source.

ADDENDUM

In the interval between the Liège meeting and the completion of this manuscript, several new observations have been reported at scientific symposia. GIACCONI, GURSKY, PAOLINI, ROSSI, and CLARK have observed clearly separate signals from Scorpius XR-1 and the galactic center region. Using a twin grid collimator array proposed by M. ODA of the Massachusetts Institute of Technology, GIACCONI and his colleagues have obtained an upper limit of 7 arc minutes for the angular diameter of Sco XR-1. G. CLARK has succeeded in measuring X-rays from the Crab Nebula in the range 15 to 60 keV, with balloon-borne scintillation counter apparatus. The spectral distribution can be fitted to synchrotron radiation with an index of about — 2. P. FISHER has observed Sco XR-1 with proportionnal counter apparatus. His spectral data would support a Planck spectrum with T $\sim 1.7 \times 10^7$ °K.

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Discussion

F. G. SMITH. — I would like to draw Friedman's attention to the recent radio occultation measurements made at Cambridge, published in " Nature ". There is a concentrated source looking similar to the X-Ray source, observed at 81 MHz and very much more strongly at 38 MHz.

The spectrum is very far from thermal in this concentrated source ; it is hard to explain the very steep spectrum between 38 MHz and higher frequencies.

D. W. SCIAMA. — Have Compton X-rays from the Crab been considered ?

R. GOULD. — In answer to Dr. SCIAMA's question on the Compton X-rays from the Crab I have estimated this flux and find a flux too small to account for the observations by a factor 10^{-6}.

G. BURBIDGE (writton down by J. L. STEINBERG). — How soon shall we get higher resolution in X rays ? The problem is very similar to that encountered in Radioastronomy.

H. FRIEDMAN. — With the stabilized Aerobee rocket, it should be feasible to fix the position of an X-ray source relative to nearby stars with an accuracy of about 1 minute of arc. We have made preliminary designs for a mechanical collimator which would provide a measure of the size of the Scorpius source with a resolution of about 0.2 minutes of arc.

L. GRATTON. — Concerning neutron star models, I wish to mention that the equation of state of a neutron gas has been investigated during the last two years by SZAMOSI and myself. It seems that by using what appears to us to be the best equation of state no appreciable difference with the original OPPENHEIMER's model can be found. I also wish to mention that Pr. FINSI, of my group, has investigated the cooling down of a neutron star by neutrino-loss ; when applied to the S. N. of 1054, his data give a temperature much too low for the observed X-ray emission.

R. L. F. BOYD. — Grazing incidence optics of the type mentioned earlier in the symposium hold good promise for the study of faint X-ray sources in future. The small field of view reduces the problem of sky background and may be expected to give location and angular size to about 1′ or better. The team of University College, London and the University of Leicester is preparing a grazing incidence telescope array for O.A.O-3.

K. A. **Pounds**. — In the Crab nebula measurement I notice from your slide that no minimum was shown between the very high counting rate obtained during passage across the Sun and the subsequent Crab measurement. Was such a minimum observed and have you been able to check yet that no radiation after-effects occur in your detectors ?

H. **Friedman**. — The Sun was 22° from the Crab. As the Sun passed through the field of the detectors, the rocket was rolling at about 6° per second. Roughly one second elapsed from the time the Sun left the edge of the field of view to the time the Crab was centered in the field. There was no opportunity, therefore, for the count to return to background. If the counts are averaged for a fraction of a second, the statistical fluctuation is too large to attach much quantitative significance to the evidence of a weak minimum. We judge from our laboratory experience with the counters and from the nearly perfect symmetry of the counting rates as the Sun entered and left the field of view that there was no significant hysteresis in the counter response or any appreciable remnant of solar flux. Furthermore, hysteresis would have produced an exponential type of decay curve rather than the observed occultation curve, which is concave toward the time abscissa.

H. **Friedman** (written down by J. L. **Steinberg**). — There are some claims of X-rays from the Moon. But after occultation of the Crab, the flux goes down to background so that there is no trace of moon X-ray emission.

J. W. **Hovenier**. — Can Dr. **Friedman** give us some information about the spectral distribution of the X-rays received from the region near the galactic centre ?

H. **Friedman**. — We have no spectral detail for the X-ray sources near the galactic center region.

W. **de Graaf**. — Dr. **Friedman** in case the X-ray radiation from the Crab nebula would be fluorescent radiation activated by a neutron star with maximum radiation around 2 Å, would you not still expect to see the remaining primary radiation of the neutron star ?

H. **Friedman**. — That portion of the neutron star spectrum to the long wavelength side of 2 Å would penetrate the nebula and appear as a point source.

W. A. **Fowler**. — In regard to possible sources of energy in the Crab, one should now add gravitational energy of collapse (réf. **Hoyle**, **Fowler**, **Burbidge**, *Ap. J.* **139** **1964**) to the previously suggested sources, namely radioactivity and neutron stars. The gravitational collapse suggestion (or speculation) introduces problems in ultra high energy physics which may prove to be of great interest, since currently operating accelerators are not able to reach the energies involved.