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SPATIAL DISTRIBUTION OF X-RAYS IN THE CRAB NEBULA*

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ABSTRACT

X-ray measurements made during a lunar occultation of the Crab Nebula show that the spatial extent of the source is about 100″ in the east-west direction. The center of the X-ray emitting region is about 8″ west of the pulsar. The shape is basically the same when viewed in several energy intervals from 0.5 to 16 keV. The size does not change by more than 30 percent over this energy range. Optical and X-ray intensity distributions are compared, and no optical features other than the pulsar are obvious in the X-ray data.

Subject headings: Crab Nebula — occultations — supernova remnants — X-ray sources

I. INTRODUCTION

Eleven years ago, on 1964 July 7, the X-ray astronomy group at the Naval Research Laboratories (Bowyer *et al.* 1964), succeeded in determining the angular size of the Crab Nebula. That experiment, performed during a lunar occultation, has become one of the classic experiments of X-ray astronomy.

The following 11 years have seen great advances in counter design, in the capability to point rocket-borne detectors, and in the ability to analyze large quantities of transmitted data. Our calculations showed that a second observation of an occultation could provide the opportunity to actually measure the spatial variations of the intensity across the nebula.

On 1974 November 3, we measured X-rays from the Crab during an occultation. The results reported here show intensity variations across the nebula, in one dimension, with a spatial resolution of 5″.

The results presented here are based on our analysis to date. The conclusions that can already be drawn from the data warrant reporting our preliminary results at this time.

II. EXPERIMENT

X-ray measurements made during an occultation are subject to many more constraints than are more typical measurements in X-ray astronomy. The precise timing of the launch, the motion of the vehicle and the Moon during the observation, the importance of the differences in counting rate rather than the counting rate itself, are all unique to the occultation experiment. We summarize below the parameters that served to define the experiment.

The contact angle of the limb of the Moon defines the direction of the "cut" across the nebula. This is fixed when the particular occultation and the geographic latitude for the observation have been specified. We wanted to observe as much of the occultation as possible, so we chose one in which the limb of the Moon, at contact, was nearly perpendicular to the direction of motion of the Moon.

The observation took place on 1974 November 3 from ERDA's Kauai test facility. The experiment was carried aboard a Strypi vehicle launched at UT 10:34:55. During the observation, the pulsar disappeared behind the lunar limb at a p.a. (position angle) of 97°.7, and the limb of the Moon was tilted about 7°.7 east of north throughout the occultation.

The detectors were thin-window proportional counters filled with the standard P-10 mixture of argon and methane. They were sensitive from 0.5 to 16 keV. A xenon detector was also included to gather information at higher energies, but unfortunately the calibration source on this counter jammed and was viewed continuously throughout the flight. Consequently, the background was very high and no useful data from the Crab were obtained from the xenon counter.

The collimated detectors were pointed directly at the Moon, and the measured X-ray flux was seen to gradually disappear as the Moon occulted the nebula. Within the limits described below, the duration of the observation was controlled by celestial mechanics. This preempted the usual option of getting more data by keeping the detectors aloft for a longer time. Thus, to obtain better data, the only option was to use as much collecting area as possible. The P-10 detectors used during this flight had a total effective area of 2900 cm^2.

A choice existed between the extent of the nebula over which the measurement was to be made and the

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spatial resolution that could be achieved. By proper choice of rocket trajectory, the apparent motion of the Moon could be accelerated or decelerated. To observe as much of the occultation as possible, the rocket's trajectory was chosen to give maximum acceleration to the apparent motion of the Moon. During the flight the limb of the Moon was observed to move from 80″ west of the pulsar to 92″ east of the pulsar.

The actual data acquired during this experiment consisted of a gradually decreasing counting rate as the Crab disappeared behind the Moon. This was one step removed from the desired result, which was the intensity distribution across the Crab. To obtain this result, there were possible errors that had to be taken into account. We consider these below.

Consider first the errors caused by a small motion of the detectors when they are supposed to be pointed steadily at the source. If this motion causes the source to drift out of the field of view, the measured flux decreases, and the result is exactly the same as if a bright part of the nebula had just been occulted. If the rocket motion causes the source to drift toward the center of the field of view, the source could seem to become brighter. Thus the motion of the vehicle must be kept to a level such that this jitter in measured flux is much less than the intensity variations to be measured.

For the present observation, the attitude control system of the rocket was controlled by a Moon sensor. The Moon sensor, designed especially for this experiment, maintained the detector pointed at the center of illumination of the Moon to an accuracy of ±0′.6. The mechanical collimators that defined the detector field of view were 2°.5 FWHM, so possible jitter of the signal was 0.4 percent.

A second source of error comes from the possibility of encountering electrons at high altitudes. Because our detectors have thin plastic windows, low-energy electrons can easily penetrate the counter and produce counts indistinguishable from X-ray counts. We have identified electron background in previous scanning observations because of symmetry of the electron flux about the magnetic-field direction. The present experiment did not scan, so there was no chance of identifying the electron background by directional dependence.

The acquired data are differentiated to derive the intensity distribution across the Crab. Thus a constant flux of electrons is subtracted out and does not contaminate the final results. The electron flux, however, varies with altitude, and a changing flux will distort the derived intensity distribution of the Crab Nebula.

Accordingly, steps were taken to protect the counters from soft electrons. The cell size of the honeycomb collimators was chosen to be especially large so that the individual channels were as deep as possible. The collimator cells were 4.75 inches (12 cm) deep. To minimize scattering of electrons from collimator walls, the cells were fabricated from 60 line-per-inch (24 lines per cm) stainless steel screen.

Magnets were built into the collimators at 2-inch (5 cm) intervals to bend the electron trajectories into the collimator walls. The entire collimator was permeated by a fairly uniform field of about 100 gauss. Also using this configuration, we compared the rejection efficiency of collimators made of several different materials using electrons from a ^{90}Sr source. The collimator of stainless steel screen was found to reject 94 percent of the electrons, while an aluminum collimator rejected only 79 percent.

At the time of launch the Crab Nebula was 70° from the direction of the local magnetic-field line. In the data there is no evident enhanced counting rate that might be caused by electrons, and we believe our electron rejection system was successful.

A third source of error comes from the uncertainty in the position of the observing platform as a function of time. The rate of the occultation is determined principally by the horizontal motion of the rocket. Uncertainty in the position of the rocket means an uncertainty in the location of the projection of the limb of the Moon on the Crab and, subsequently, a decrease in the spatial resolution of the measurement.

For an estimate of this error, we relied on the accuracy of the radars used to track the vehicle. In the worst possible case, the accepted accuracy in these systems would result in an uncertainty of ±0″.15 in the location of the limb of the Moon. This conservative figure is good for any point on the trajectory.

Thus, if our electron rejection was effective, the errors involved are small with respect to the parameters we were trying to measure. Counting statistics remain the dominant uncertainty, and it is this effect that ultimately limits both the spatial resolution and the accuracy of the derived intensity distribution.

Data analysis involves taking differences between the fluxes measured at successive times. The faster the flux falls off, the greater was the intensity of that part of the nebula just occulted. The problem is that the resultant intensity, a small number, is subject to the statistical uncertainties of the large numbers that were subtracted. It is this effect that ultimately determines how small a difference in time, i.e., how small a "slice" of the nebula, can be used to derive a value for the intensity. The spatial resolution was

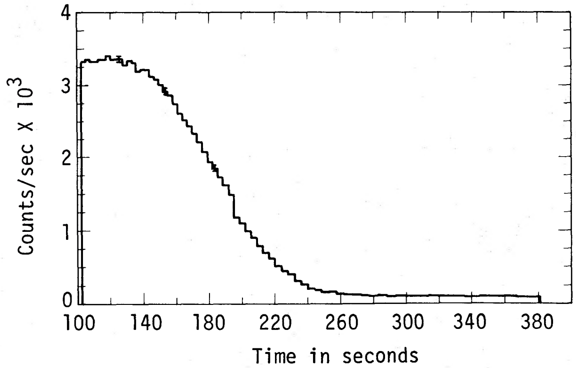

FIG. 1.—This plot shows the occultation progressing during the flight. The energy range is from 2 to 3.5 keV.

chosen subjectively to give reasonable statistics for the derived values of the intensity.

III. RESULTS

Figure 1 shows a plot of the measured flux as it developed with time during the flight. The Crab was acquired at 100 s into the flight, and it showed unocculted for about 20 s before the shadowing started. A discontinuity in the measured flux can be seen at 193 s when the pulsar blinked out.

The relative motion of the Moon across the nebula gradually slowed down all through the observation. After 220 s it was moving very slowly. Thus two effects are present in the data shown in Figure 1. The intensity distribution across the Crab is nonuniform, and the rate at which the shadowing occurs is also nonuniform.

Figure 2 shows a photograph of the continuum radiation from the Crab as it appeared on 1974 October 18, 16 days before the X-ray observation. The photograph was obtained at Kitt Peak using the no. 2 36-inch (91 cm) telescope with image tube. The wavelength band was 90 Å wide and centered at 4760 Å. No Polaroid filter was used, and the exposure was 40 minutes.

Superposed on the photograph are lines that represent the limb of the Moon. The lines are stepped at 10″ intervals to show the progress of the limb

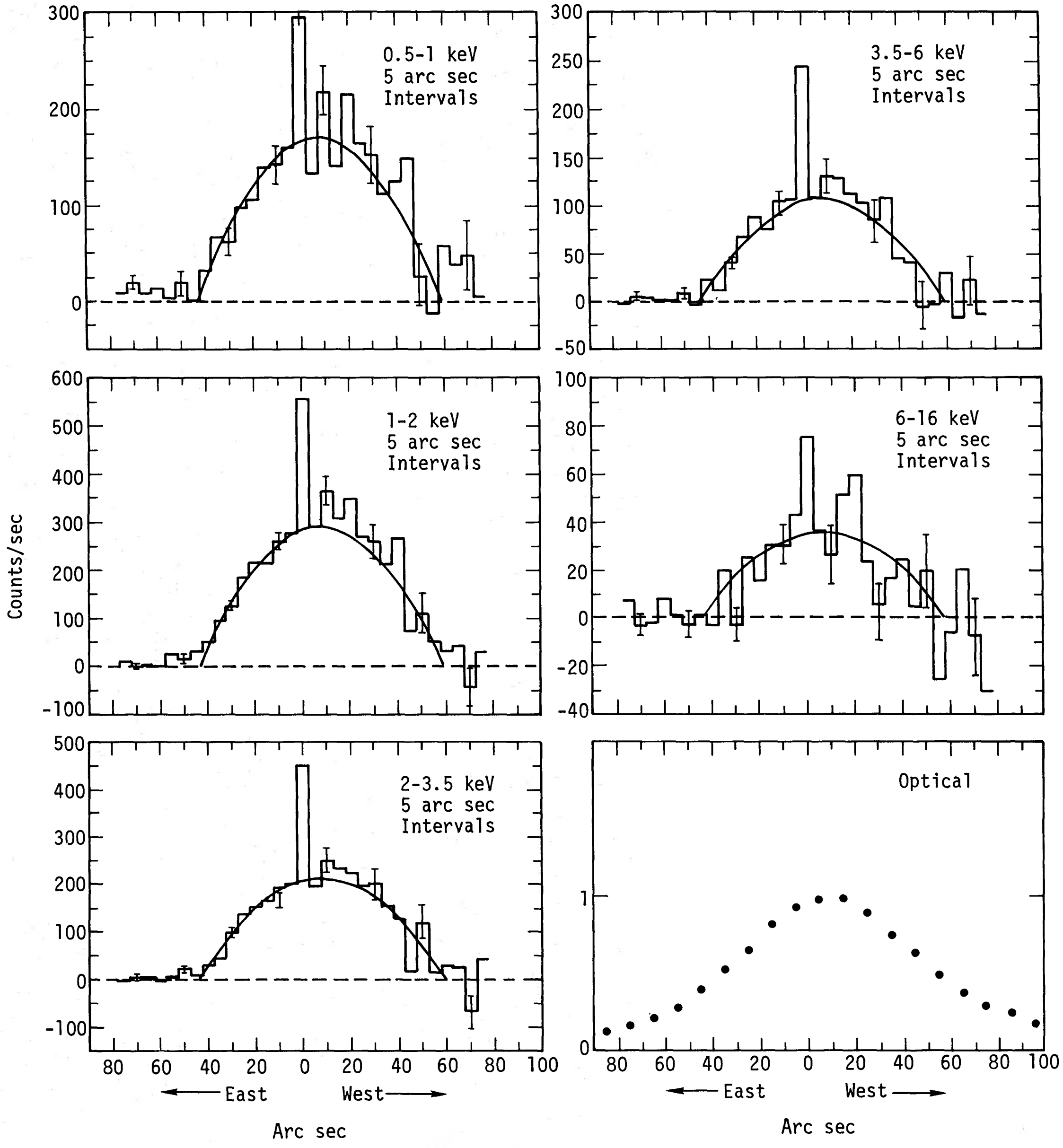

FIG. 3.—The intensity distribution across the Crab Nebula in several energy intervals. The position of the pulsar is used as the origin of the angular scale. A spherical source with constant emissivity would produce the parabolic intensity distribution superposed on the data. In each case, the parabola is 102″ wide at base and is centered at 8″ west of the pulsar.

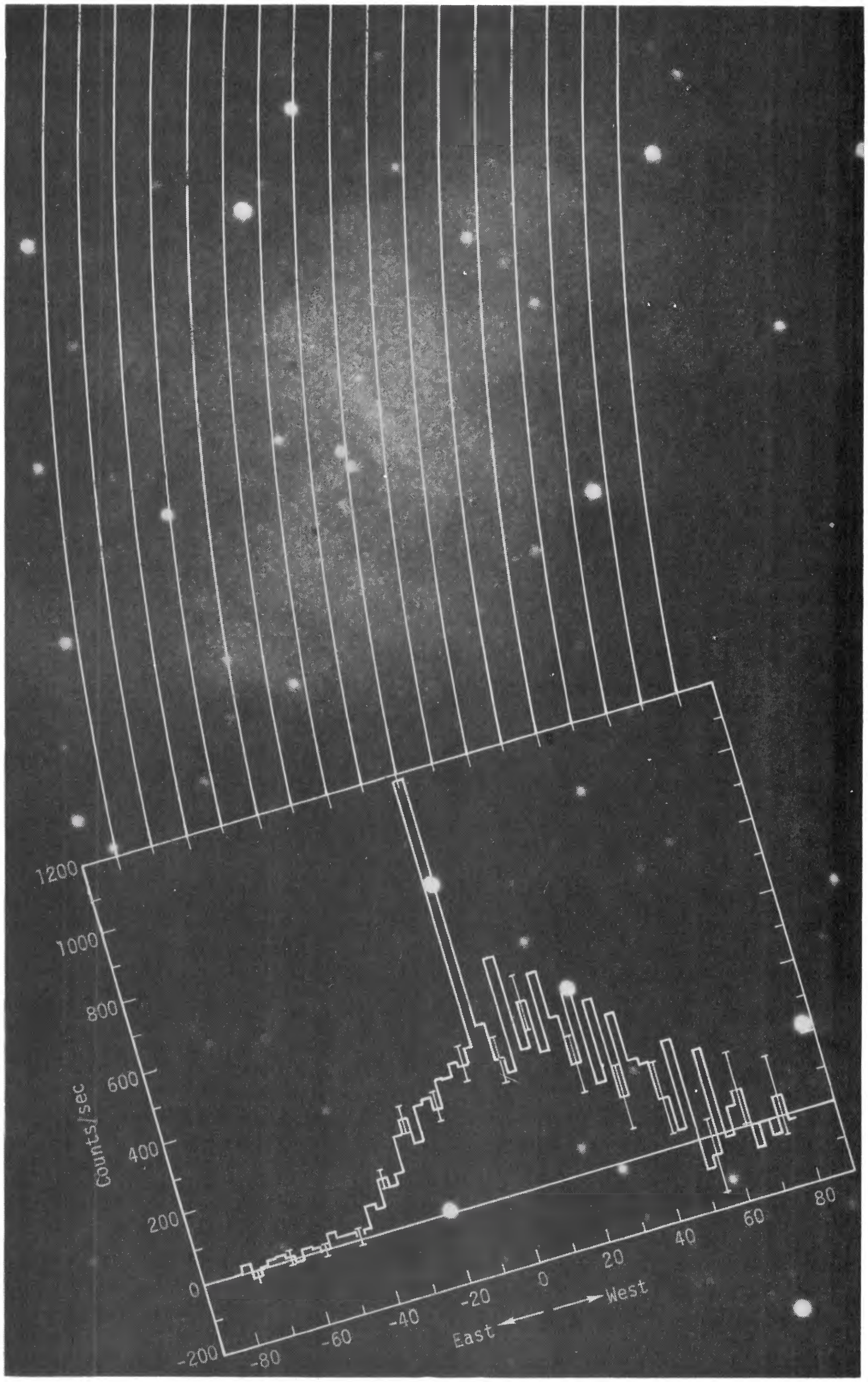

FIG. 2.—The intensity distribution across the Crab Nebula. The data shown below the photograph encompass the entire energy interval from 0.5 to 16 keV. The spatial resolution is 2ʹ.5. The position of the pulsar is used as the origin of the angular scale.

during the flight. These lines ignore the mountains and valleys that actually define a ragged contour of the lunar limb. The deviations from circularity are of the order of $\pm 1''$. Thus the strips of the nebula that we will consider do indeed have somewhat blurred edges. This effect would be very important if the X-ray emission came from a collection of point sources. Then their location would be correspondingly uncertain. Since the emission is found to be diffuse, the ragged edge of the Moon has only a small effect on our results.

A plot of the reduced data, summed over the interval 0.5 to 16 keV, is shown below the photograph. With all the data contributing to the plot, it is possible to present spatial bins that are only $2''.5$ in the east-west direction. An obvious feature of the plot is that the error bars are larger on the western side than they are in the east. This is because the measured flux was greater here, and the derived intensity results from subtracting large numbers. Another feature arising from the finite-difference scheme is that the statistical jitter in the data can result in negative values of the derived intensity. Again, these values are consistent with zero intensity.

The nebular intensity seems to rise to a substantial value, about half the maximum intensity of the nebula, at around 45″ west of the pulsar. Looking at the lines drawn on the photograph, it is in this region that the optical emission becomes more intense. East of the pulsar the intensity decreases more uniformly, but the X-ray nebula extends only to 40″ east, again at the end of the region of intense optical emission.

Figure 3 shows the data in finer energy intervals, but in coarser spatial intervals. This reflects the smaller number of counts that contribute to each of the separate plots. A striking feature of these individual plots is the peak caused by the pulsar. The relative amount of pulsed radiation is the subject of continued analysis. Results on this and other aspects of measurements of the pulsar will be forthcoming.

A second feature in these plots is that the western slope of the intensity distribution seems to have more structure than the eastern slope. There appear to be local enhancements from 10″ to 20″ west of the pulsar and from 35″ to 45″ west of the pulsar. However, since the error bars are larger in the western half, these suggested features must await future verification.

The optical intensity distribution is also shown in Figure 3. This result was obtained by making an isodensity plot of the photograph in Figure 2 and then integrating the intensity along each long strip. It is clear that the extent of the X-ray nebula is less than that of the optical nebula. The extent of the X-ray nebula is less than that of the optical nebula. The extent of the X-ray nebula is seen to be about 100″ in the east-west direction.

IV. DISCUSSION

Scargle (1969) has extensively discussed the optical activity in the Crab Nebula. A series of wisps, varying in size and brightness, have been observed superposed on the continuum. These wisps move with a velocity of about 10″ per year. The radiation is highly polarized. It is accepted to be synchrotron radiation from relativistic electrons moving in a magnetic field. The optical activity is taken to be a manifestation of hydromagnetic activity through the nebula with regions of compressed field showing as wisps.

The X-ray emission is centered at, and symmetrical about, the region of maximum optical activity. Indeed, maximum X-ray emission and maximum optical emission in the continuum are both centered west of the pulsar at about the position of Scargle's "wisp 1," the brightest, most persistent of the wisps. This reinforces our belief that the optical activity, the optical continuum, and the X-rays are all caused by the same underlying fundamental processes.

However, we do not clearly see any of the optical wisps in the X-ray data. The only hint of such an association is that the X-ray intensity rises rather abruptly in the western half of the nebula, where the brightest wisps are found. It should be noted, however, that the direction of the cut across the nebula is such that even the optical data do not show up the wisp structure. The exact association of X-rays with wisps is thus left undetermined by these data.

Electrons with energy around 4×10^4 GeV in a magnetic field of 10^{-4} gauss will emit radiation at X-ray wavelengths. However, since they have short lifetimes (<20 yr), a continuous supply of these electrons or a continuous acceleration mechanism is required. The obvious source of these electrons is the pulsar. The fact that the diffuse X-ray source is not centered on the pulsar, however, indicates that the mechanism by which the pulsar transfers energy to the electrons is not simple.

Consider the shape of the X-ray nebula. The intensity distribution measures how the emission is distributed within the volume of the nebula. We have calculated this distribution for three simple models. In the first case the emissivity is constant throughout

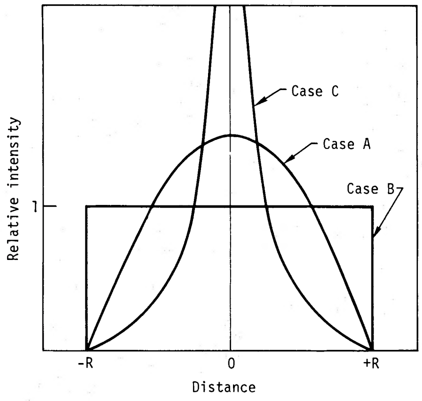

FIG. 4.—The results of the calculated intensity distribution that would be observed by passing a slit across a radiating sphere. Case A is for a sphere uniformly filled with radiation; case B is for a shell source; and case C is for an emissivity that varies as r^{-2}.

the volume of a sphere. In the second case the radiation comes from a spherical shell of small thickness compared with the radius. In the third case the emissivity varies as r^{-2}. When we integrate along strips to compare the result with our observation, the intensity distributions are as shown in Figure 4. The curves in Figure 4 have been normalized to have the same area.

The parabolic curve, based on a uniform-volume emissivity, much more closely resembles the actual data than do the other two. Thus the observed shape of the intensity distribution in the Crab is suggestive of a source whose emissivity is constant throughout. Returning to Figure 3, a parabola has been superposed on each set of data. The parabolas are each centered 8″ west of the pulsar and are each 102″ at base.

We note that the size of the nebula does not change rapidly with energy. In the interval from 0.5 to 16 keV, the size certainly does not change by more than 30 percent. We are presently performing the analysis necessary to determine more accurately the variation of the size of the nebula with energy.

We now reject the simple model in which energetic electrons originate at the pulsar and radiate as they propagate outward through a magnetic field. If the field were strong close to the pulsar and became weaker as the distance from the pulsar increased, the X-ray distribution would be sharply peaked. Case C in Figure 4 represents the intensity distribution for the magnetic field varying as $r^{-1/2}$.

If the field in the nebula were uniform, the electrons would continuously lose energy as they propagated outward, and the high-energy source would appear appreciably smaller than the low-energy source. Figure 3 eliminates this possibility.

If there were a large bubble in the nebula, with the magnetic field concentrated at the edge, the size of the source would be constant with energy but the intensity distributions across the nebula would be flat-topped. Again, this is not the case.

We conclude that the acceleration of electrons must be taking place throughout the volume of the nebula. The pulsar might provide the mechanism, such as plasma waves, and the energy for this acceleration. Only by invoking such an intermediate mechanism can we explain the existence of high-energy electrons throughout the emitting volume.

V. COMPARISON WITH OTHER RESULTS

Eleven years ago a lunar occultation of the Crab was observed in the energy range of 1 to 6 keV by Bowyer *et al.* (1964). This was followed by modulation-collimator observations of Oda *et al.* (1967) in the energy range 1 to 6 keV and of Floyd (1970) in the range 25 to 100 keV. These three observations all showed that the source was extended approximately 1′ to 2′ in size.

The latest series of lunar occultations have been observed in the energy range 2.5 to 7.5 keV by a detector on the *Copernicus* satellite (Davison *et al.* 1975) and in the energy range 20 to 150 keV with a balloon-borne detector (Ricker *et al.* 1975). Both these observations find the source to be centered about 10″ northwest of the pulsar. The *Copernicus* source extends along our coordinate (p.a. 98°) from approximately −20″ to +55″, measured from the pulsar. This is in complete agreement with our observation and is expected because the energy ranges of the two observations are similar. The satellite data have too few counts to allow determination of the shape or exact boundaries of the source.

The balloon result (MIT), however, is at an average energy of approximately 50 keV. They find an extended source of dimension $(24 \pm 7)'' \times (49 \pm 7)''$. This defines the parallelogram that is superposed on a picture of the Crab to illustrate the extent and location of the source (Ricker *et al.* 1975). Their data for each p.a. have been fitted assuming a Gaussian shape. The above dimensions are full widths at half-maximum (FWHM) of this Gaussian. Thus along each p.a. the above dimensions include 76 percent of the observed diffuse X-ray emission. Is this compatible with the shape and extent of the source derived from our data, or do these higher energy data require a smaller extended source?

The parallelogram containing the MIT source extends from −15″ to +25″ along our coordinate. In this region 55 percent of our counts are caused by the diffuse source. The uncertainties in the MIT observation are such that the dimensions of the parallelogram can be made larger. If the size is increased by 1 σ, it extends from −20″ to +30″ and includes 70 percent of our counts. It appears then that the source at about 50 keV is smaller than the source measured by us at p.a. 98° and energy 0.5 to 6 keV. The MIT observation, compared with ours, however, is not conclusive. If the parallelogram is extended 2 σ in size, the 50 keV data are compatible with the shape and extent of the source that we observe.

VI. SUMMARY

We have been able to measure the intensity distribution in one dimension across the Crab Nebula. We find that the source is diffuse and that the X-ray size of the nebula is smaller than the optical size. The X-ray source is centered at, and is symmetrical about, a point located approximately 8″ west of the pulsar. Thus maximum X-ray emission appears to come from the region of maximum optical activity. The intensity of the optical continuum radiation also is maximum and is centered west of the pulsar.

The shape of the source and the small dependence of size on energy show that the source emits throughout its volume. Probably the acceleration of electrons also takes place throughout the volume of the source.

The results reported here represent only one aspect of the information obtained on 1974 November 3. In particular, we shall report our findings about the pulsar at a later date.

We wish to thank R. Chevalier and the Kitt Peak Observatory for the photograph in Figure 2. Credit for the experiment package goes to the engineers and technicians of LLL.

Sandia Laboratories provided the vehicle, the launch support, the payload, including telemetry and attitude control systems, the recovery section, and the recovery operation. In particular, we are thankful for Sandia's ability to respond to technical and administrative problems that occurred very close to the launch date. That the launch occurred at all was the result of an enormous amount of last minute work by H. Wente of Sandia.

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