

DETECTION OF X-RAY POLARIZATION OF THE CRAB NEBULA

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ABSTRACT

Two different types of X-ray polarimeters were used in a sounding rocket to search for X-ray polarization of the Crab Nebula. Polarization was detected at a statistical confidence level of 99.7 percent. If the X-ray polarization is assumed to be independent of energy, the results of this and a previous experiment lead to a polarization of (15.4 ± 5.2) percent at a position angle of $156^\circ \pm 10^\circ$. This result confirms the synchrotron model for X-ray emission from the Crab Nebula.

I. INTRODUCTION

The mechanism responsible for the continuum emission from the Crab Nebula is generally accepted to be synchrotron radiation. Measurements of the spectral shape and of the polarization of the radio and optical emissions are consistent with this hypothesis. Furthermore, the X-ray spectrum appears to be a natural extension of the lower-frequency synchrotron spectrum (Woltjer 1964). However, the shape of the continuum spectrum does not uniquely determine the X-ray emission mechanism. For example, Sartori and Morrison (1967) have presented a model in which the X-rays from the Crab Nebula are produced by a dilute plasma at two characteristic temperatures. In this model, however, the X-rays are unpolarized. A positive test of the hypothesis that the X-ray emission from the Crab Nebula is produced by synchrotron radiation would be provided by the observation of appreciable linear polarization of the X-ray continuum. In this paper we report the results of such an observation.

The experiment involved two types of X-ray polarimeters which were launched in an Aerobee-350 sounding rocket at 1934 UT on 1971 February 22 from Wallops Island, Virginia. One of these polarimeters was a larger version of the Thomson-scattering polarimeter used in previous experiments (Angel *et al.* 1969; Wolff *et al.* 1970; Novick, Angel, and Wolff 1971). Briefly, the instrument utilizes the angular dependence of Thomson scattering on the polarization of the incident photon. If observed at 90° with respect to the incident flux, photons are scattered preferentially in a direction orthogonal to their electric vector. Twenty-eight blocks of metallic lithium were used to incoherently scatter the incident flux into 52 beryllium-window proportional counters placed on the sides of the blocks. Thus, two orthogonal components of the polarization vector are measured simultaneously. In use, the entire rocket and therefore the polarimeter are rotated about the line of sight to the source. If the X-rays are linearly polarized, there will be a modulation of the detected signal at twice the rotation frequency. Solid-angle factors limit the amplitude of modulation to 32 percent for 100 percent polarization, in the absence of a constant background signal. The energy sensitivity in this experiment is limited below 5 keV by photoelectric absorption in the lithium and above 20 keV by the decreasing flux from the nebula.

The other polarimeter made use of the polarization dependence of Bragg reflection. The instrument consisted of four large (26.6 inch $\times$ 9.5 inch [66 $\times$ 24 cm]) panels of graphite crystals. These panels were mounted on doors set at 90° intervals around the circumference of the rocket with the long dimension of each panel parallel to the rotation axis. The doors opened to an angle of 45° with respect to this axis when the payload was above the atmosphere. The crystals reflect that portion of the incident spectrum

that satisfies the Bragg condition and whose polarization component is normal to the plane defined by the directions of the incident and reflected X-rays. Each crystal panel was slightly curved to concentrate the reflected X-rays, thus minimizing the size of the detector and the amount of cosmic-ray-induced background. The reflected X-rays were detected by a multiwire proportional counter with four 1-mil beryllium windows and a single gas volume filled with a mixture of Ne, Xe, and CO₂. Again, two orthogonal components of polarization are measured; polarized X-rays will produce a modulation of the detected signal at twice the rotation frequency of the rocket. For this polarimeter, 80 percent modulation is equivalent to 100 percent polarization in the absence of any background signal. The energy sensitivity of this instrument is determined by the Bragg condition, by the crystal material, and by the orientation of the crystals with respect to the incident flux. In this experiment data were obtained from a narrow bandwidth centered at 2.6 keV. The instrument will be described in detail elsewhere (Weisskopf *et al.* 1972).

Both polarimeters made use of pulse-height discrimination, pulse-shape discrimination, and anticoincidence veto in order to reduce the cosmic-ray-induced background.

II. IN-FLIGHT PERFORMANCE

During flight, the rocket was pointed to within 9' of the Crab Nebula by means of an offset star tracker using ζ Tau as a reference. After acquisition, control of the vehicle was transferred to a system of rate-integrating gyros, and the star tracker was jettisoned. The rocket was then rotated about the line of sight to the nebula at 5.5 s⁻¹.

Several factors contributed to limit the sensitivity of the experiment. First, the vehicle underperformed, reducing the observation time to 247 s. Second, the background encountered was much higher than had been anticipated prior to launch.¹ Finally, one of the two telemetry systems failed, resulting in a loss of half the data from each experiment. The data obtained from the lithium polarimeter were almost equally divided between orthogonal detector systems. Similarly, the data from the crystal polarimeter were obtained from two orthogonal crystal panels. In spite of the limitations described above, positive evidence for polarization was obtained.

III. ANALYSIS OF FLIGHT DATA

The summed data from orthogonal lithium polarimeter detectors and from each of the two crystal polarimeters were separately fit by a least-mean-square technique to the function

$$R(\phi_i) = S_0 + S_1 \cos \frac{\omega}{\omega_0} \phi_i + S_2 \sin \frac{\omega}{\omega_0} \phi_i, \quad (1)$$

where $R(\phi_i)$ represents the observed counting rate during the i th 5° angular rotation ϕ_i of the rocket measured from the beginning of the roll maneuver, S_0 is the average X-ray and background intensity, and ω_0 is the rotation frequency of the rocket. The data were analyzed over a range of frequencies ω ; the results for $\omega = 2\omega_0$, the signature of polarization, are listed in table 1. The parameters S_0 , S_1 , and S_2 are related to the modulation M by $M = (S_1^2 + S_2^2)^{1/2}/S_0$ and to the position of a fiducial on the rocket, ϕ' (in celestial coordinates), when the counting rate is a maximum, by $\phi' = -\frac{1}{2} \tan^{-1}(-S_2/S_1)$.

The errors listed in table 1 are 1 standard deviation based on the scatter of the data points about the best fit. The differences in the average intensities S_0 are due, in the case of the crystal polarimeters, to a preset difference in the background-rejection efficiency of the two pulse-shape discriminators and, in the case of the lithium polarimeter, to an

¹ The background rates were 0.014 and 0.0045 counts cm⁻² s⁻¹ keV⁻¹ at 1–7 keV and 6–26 keV, respectively. These rates are factors of 7 and 1.3 greater than those encountered at White Sands, New Mexico, with similar instruments employing identical background-suppression techniques. The high background rates are most certainly associated with the geomagnetic coordinates of Wallops Island, Virginia, and should be considered in determining the launch site for future X-ray experiments.

TABLE 1
BEST FIT OF THE RAW DATA TO $R(\phi) = S_0 + S_1 \cos 2\phi + S_2 \sin 2\phi$

Experiment	S_0 (counts s ⁻¹)	S_1 (counts s ⁻¹)	S_2 (counts s ⁻¹)	M (%)	ϕ'^* (°)
Crystal Door 2.....	6.99 ± 0.18	$+0.37 \pm 0.24$	-0.52 ± 0.26	9.1 ± 3.6	-27 ± 11
Crystal Door 3.....	8.08 ± 0.17	-0.18 ± 0.24	$+0.18 \pm 0.24$	3.1 ± 3.1	$+67 \pm 28$
Lithium- $X^\dagger$	99.23 ± 0.59	-0.40 ± 0.84	-1.64 ± 0.80	1.7 ± 0.8	-51 ± 14
Lithium- $Y^\dagger$	128.70 ± 0.74	-1.49 ± 0.99	$+0.38 \pm 1.11$	1.2 ± 0.8	$+83 \pm 21$

* The phase angle ϕ' is the position of a fiducial on the rocket in celestial coordinates when the counting rates in the detectors associated with the experiments listed in the first column are a maximum.

† The two orthogonal sets of lithium polarimeter detectors are labeled X and Y . The lithium polarimeters differed in azimuthal orientation from the crystal polarimeters by 9° .

unequal number of detectors. It is encouraging to see, particularly in the case of the crystal polarimeter, that the modulation measured by orthogonal detectors is consistent with a 90° phase difference, which is what one would expect in the observation of a polarized source. We must emphasize, however, that the statistical uncertainties are too large to draw any definite conclusions regarding evidence for polarization if the four independent experiments are treated separately. Accordingly, the data from each crystal polarimeter were weighted and combined. The data from the lithium polarimeters were similarly treated. These results are plotted in figure 1 and listed in table 2. The solid lines in figure 1 are the best fit to equation (1) with $\omega = 2\omega_0$. If the modulations are produced by polarization, then the corresponding position angle θ for the electric vectors are those listed in table 2. The position angles are related to the phase angles ϕ' by the relative orientation of the instruments in the rocket.

As the modulation is positive-definite, there is always a finite probability of obtaining a nonzero measurement of this quantity in the observation of an unpolarized source. The

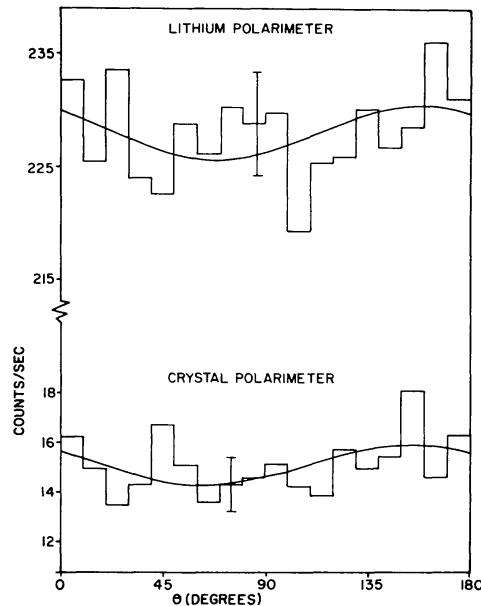


FIG. 1.—Flight data from the lithium and crystal polarimeters versus position angle θ modulo 180° . The solid lines are the best fits to a function periodic at twice the rotation frequency of the rocket.

TABLE 2
SUMMARY OF MODULATION AND POSITION-
ANGLE MEASUREMENTS

Polarimeter	M (percent)*	$\theta(^{\circ})$
Crystal.....	5.5 ± 2.3 (0.062)	155 ± 11
Lithium.....	1.1 ± 0.6 (0.177)	156 ± 14

* The modulation uncertainties are obtained from the residuals in the least-squares-fitting procedure. The quantities in parentheses are the probabilities that these modulations arose from statistical fluctuations of unmodulated data.

probabilities that the observed modulations were produced by statistical fluctuations of unmodulated data were determined by Monte Carlo simulation of the experiment and are also listed in table 2.

A cross-correlation analysis between the crystal and lithium data was performed which graphically indicates those frequency components common to both instruments. In this analysis the average counting rate $\langle r \rangle$ is subtracted from the data points. These residuals for each type of polarimeter are then multiplied and summed according to equation (2) which defines the cross-correlation function $f(\phi_i)$:

$$f(\phi_i) = (36\langle r_{Cr} \rangle \langle r_{Li} \rangle)^{-1} \sum_{j=1}^{72} \{r(\phi_{i+j-1})_{Cr} - \langle r_{Cr} \rangle\} \times \{r(\phi_j)_{Li} - \langle r_{Li} \rangle\}, \quad (2)$$

where $r_{Cr,Li}(\phi_k) = R_{Cr-2,Li-X}(\phi_k) + R_{Cr-3,Li-Y}(\phi_k + \frac{1}{2}\pi)$ and the subscripts Li and Cr refer to the lithium and crystal polarimeters, respectively. If modulation at a common frequency has been detected by both instruments, then one expects modulation of the cross-correlation function as the relative phase (the index i in eq. [2]) between the two polarimeters is varied. Furthermore, the amplitude of this modulation should be the product of the individual modulations. The frequency distribution of the absolute magnitude of the amplitude of the cross-correlation function for the flight data is shown in figure 2a. The peak at $2\omega_0$ in the analysis of the flight data is evident. The broad width of the peak was shown by computer simulation to be consistent with the limited data set and the 5.5 and 1.1 percent modulation measured by the two polarimeters.

The cross-correlation function is plotted in figure 2b. The solid line in the figure is the best fit to a periodic function at $2\omega_0$. The amplitude of modulation of the cross-correlation function is $(6.16 \pm 1.78) \times 10^{-4}$ in excellent agreement with the product of the modulations listed in table 2. The probability that this result occurred by chance is 0.03. Therefore, we can state with 97 percent confidence that both instruments have detected modulation of the signal at twice the frequency of rotation of the rocket.

Furthermore, we note that for random data any position angle between 0° and 180° is equally probable. On the other hand, if the modulations measured by the two types of polarimeters are produced by a true physical effect for which the phase is the same, then we expect the measured position angles to be identical. The fact that the observed difference in the position angles is $(1 \pm 18)^{\circ}$ can be used to increase the statistical confidence level of the results. The joint probability that statistical fluctuations of unmodulated data produced the measured modulations at the same phase (within the error) is 0.003. Therefore, disregarding for the moment possible systematic effects, we can conclude with 99.7 percent confidence that the two polarimeters have detected linearly polarized X-rays at the same position angle.

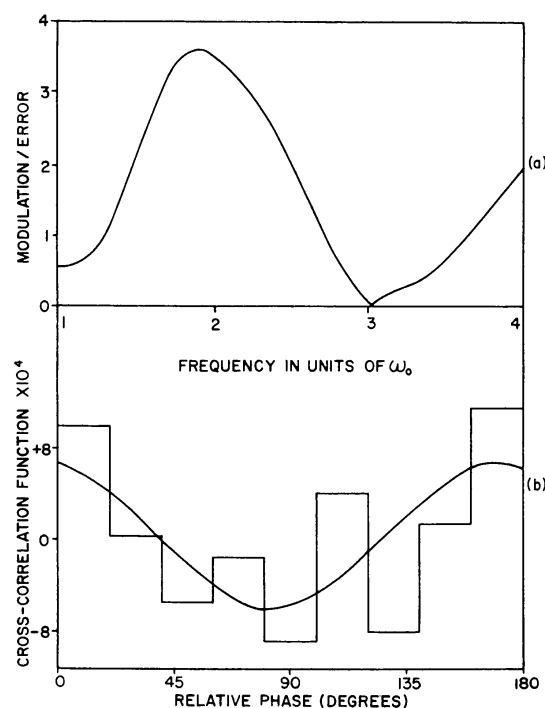


FIG. 2.—(a) Frequency distribution of the absolute magnitude of the amplitude of the cross-correlation function. The amplitude is normalized to 1σ . (b) The cross-correlation function versus relative phase ϕ modulo 180° . The solid line is the best fit to a function periodic at twice the rotation frequency of the rocket.

IV. SYSTEMATIC EFFECTS

Systematic effects fall into two distinct categories: those associated with a possible anisotropy of the primary cosmic-ray flux, such as the east-west effect; and those associated with a pointing inaccuracy of the rocket and/or misalignment of the instruments with respect to the axis of the vehicle.

If the $2\omega_0$ component of modulation measured by the crystal polarimeter is attributed to an anisotropy associated with the cosmic-ray-induced background, then one would expect to measure an increase in the modulation as the amount of background is increased. Analysis of the data with the various background-suppression criteria removed showed a decrease in the modulation from (5.5 ± 2.3) percent to (0.4 ± 0.5) percent as the ratio of the background to the signal was increased by a factor of 28. Furthermore, the dependence of the measured decrease in modulation as a function of the signal-to-background ratio was precisely what one would expect from a modulation of the X-ray signal in the presence of an unmodulated background.

Comparable information of sufficient statistical significance was not available to perform a similar analysis for the lithium polarimeter. The modulation measured by this polarimeter might also be interpreted as arising from the east-west effect. Under this interpretation the data are consistent with the presence of a flux of positively charged particles moving toward $66^\circ \pm 14^\circ$ east from north. However, analysis of a comparable body of data in a higher-energy bandwidth, 17–26 keV, which contained practically no X-ray data, showed a decreased modulation of (0.8 ± 0.7) percent. Though effectively at the same position angle, $42^\circ \pm 24^\circ$, the probability that this result was produced by unmodulated data is 0.46, a factor of 3 greater than that for the data listed in table 2. While not entirely conclusive, the result is certainly indicative of an unmodulated background signal. Furthermore, if such a background effect were present, then because of

asymmetries in the payload, we would also expect a common modulation at ω_0 in the two energy bands. While we find such components at similar statistical levels to those at $2\omega_0$, the position angles in the two bands differ by $108^\circ \pm 37^\circ$, a result completely inconsistent with an anisotropic background.

Spurious modulation of the detected signal may also occur if there is a sufficient misalignment of the axis of rotation of the polarimeters and the direction to the X-ray source. As mentioned previously, a star tracker and rate-integrating gyro system were used to point the payload to within $9'$ of the source. The pointing stability as measured during the flight was better than $9''$.

The principal effect of a pointing inaccuracy in the lithium polarimeter is to allow unscattered photons to pass directly through the lithium blocks into the proportional counters. As the signals from the detectors on opposite sides of a block are summed together, these unscattered photons will introduce a spurious modulation at $2\omega_0$ as the rocket rotates. A laboratory calibration of the instrument showed that, for misalignment of as much as 3° and the signal-to-background ratio encountered during the flight, such an effect would produce at most 0.25 percent modulation, well below the sensitivity of the experiment.

As the use of the focusing technique would imply, the crystal polarimeter is much more sensitive to pointing inaccuracies than the lithium polarimeter. One effect of a pointing error is to produce a wandering of the image in the focal plane as the rocket precesses about the line of sight to the source. The active area of the detector was made large enough to tolerate pointing inaccuracies of as much as 2.5° and still retain the entire image within the field of view. Spurious modulation may also arise from the combined effects of a pointing error, producing motion of the image and a spatially nonuniform detector response. A calibration was performed which showed that for misalignments of as much as 0.25° such an effect could account for at most 0.3 percent modulation. A further effect of a pointing error is to introduce variation of the effective geometric area and the Bragg angle of each crystal as the rocket rotates. Examination of the relevant formulas showed that even a pointing error of as much as 3° would only produce a spurious modulation of 1 percent.

In summary, the data from the crystal polarimeter were shown to be free from systematic effects. In the case of the lithium polarimeter we can definitely exclude all systematic effects except possibly that arising from the east-west anisotropy. On the other hand, the strong agreement between the position angles measured by the two types of polarimeters and the analysis of the high-energy bandwidth of the lithium polarimeter cast serious doubt that this instrument was sensitive to this effect.

V. POLARIZATION

The modulation of the detected signal can be converted to polarization by subtracting the non-X-ray background and correcting for the fact that 100 percent polarization would produce 32 and 80 percent modulation in the lithium and crystal polarimeters, respectively. Not enough time was spent off-target to provide for a statistically significant independent measurement of the background spectrum. The data from the previous flight of a lithium polarimeter (Wolff *et al.* 1970), in which the response of this instrument to X-rays from the Crab Nebula was measured to 5 percent, were used to determine the signal in the present experiment. This was the first flight of the crystal polarimeter, and comparable data were not available. In this case, the spectrum from the nebula (Gorenstein, Kellogg, and Gursky 1969) was folded through the known response of the instrument to determine the signal strength. The results of this calculation were estimated to be in error by at most 20 percent. This error was ignored in converting the modulation to polarization. The effect of an uncertainty in the signal strength is to change the values of the polarization P but it does not change the statistical significance of these measurements, P/σ_P . The position angles are, of course, independent of the

TABLE 3
SUMMARY OF STOKES PARAMETERS AND X-RAY POLARIZATION OF THE CRAB NEBULA

Experiment	Energy Range (keV)	q (percent)	u (percent)	P (percent)	θ (degrees)
Bragg crystal polarimeter, 2/22/71..	2.0- 3.2	15.4 ± 9.8	-18.5 ± 10.1	24.1 ± 10.2	155 ± 11
Lithium polarimeter, 2/22/71.....	7.0-17.0	9.5 ± 7.7	-11.2 ± 7.9	14.7 ± 7.9	155 ± 14
This experiment combined,* 2/22/71	...	11.8 ± 6.1	-13.9 ± 6.2	18.2 ± 6.1	155 ± 10
Lithium polarimeter,† 3/7/69.....	5.5-22.0	7.2 ± 9.5	-5.0 ± 9.5	8.8 ± 9.5	163 ± 29
All X-ray data,*	...	10.5 ± 5.1	-11.3 ± 5.2	15.4 ± 5.2	156 ± 10

* Assumes that the polarization is energy independent.

† Wolff *et al.* 1970.

signal strength. The polarization results for this and the previous polarization experiment (Wolff *et al.* 1970) are summarized in table 3.

If we assume that the polarization is independent of the energy, the results of this experiment and the previous experiment can be combined to yield a polarization of the Crab Nebula of (15.4 ± 5.2) percent at a position angle of $156^\circ \pm 10^\circ$. This is to be compared to the polarization in the optical of 14 percent at a position angle of 154° when averaged over the X-ray-emitting region, which for the present purpose is assumed to be $1'$ in radius (Woltjer 1972).

VI. CONCLUSION

Two completely different types of X-ray polarimeters were used to measure the X-ray polarization of the Crab Nebula. Each instrument measured modulation of the detected signal, the signature of polarization, at a confidence level of 82 and 94 percent. A cross-correlation analysis was performed which showed (at a confidence level of 97 percent) that these results were not produced by statistical fluctuations of unmodulated data. The fact that both polarimeters measured modulation at the same position angle was used to increase this confidence level to well over 99 percent. Several possible systematic events were examined, and the data from the crystal polarimeter were shown to be free from such effects. Arguments were presented which showed that it was highly improbable that the data from the lithium polarimeter were produced by any systematic effect.

If the results of this and our previous experiment are combined, they lead to an average X-ray polarization of the Crab Nebula of (15.4 ± 5.2) percent at a position angle of $156^\circ \pm 10^\circ$. This result is in excellent agreement with the optical polarization when averaged over the X-ray-emitting region of the nebula and provides conclusive evidence for the synchrotron emission mechanism.

The X-ray pulsar NP 0532 was also observed. The contribution to the data from the pulsar was too small to influence the results for the nebular emission. An upper limit to the polarization of the pulsar will be discussed elsewhere.

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