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SCOPE B. EXPERIMENTAL X-RAY ASTRONOMY

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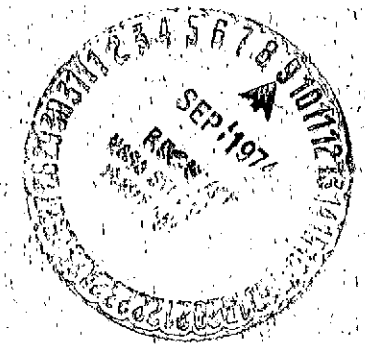

C O N T E N T S

PREFACE

The program in experimental X-ray astronomy at Columbia University was initiated as early as mid-1964. Support for this work by the National Aeronautics and Space Administration, Goddard Space Flight Center Institute for Space Studies, began 1 August 1966 under the grant NsG 445, entitled "Multidisciplinary Research in the Space Sciences. Scope B. Experimental X-Ray Astronomy," and was continued under the successor grant NGL 33-008-012, Scope B, until 10 January 1973. Beginning 1 January 1968, concurrent support for this program has been provided and is continuing under NASA grant NGR 33-008-102, entitled "X-Ray Astronomy," monitored by the Physics and Astronomy Branch, Code SG, NASA Headquarters, Washington, D. C. 20546.

In this final technical report we summarize work completed under grant NGL 33-008-012, Scope B, for the period from 1 August 1966 to 10 January 1973. A large share of the effort in the early years of the program was devoted to the design and development of instruments suitable for rocket-borne X-ray astronomy experiments. Successful designs that were implemented are summarized in Section I.B. They include a large-area modular X-ray focusing system, incoherent-scattering polarimeters, Bragg crystal spectrometers and polarimeters, and a focusing collector for long wavelength X-ray astronomy. The applications of these instruments to the observation of X-ray sources in rocket-borne experiments are given in Section I.C. Observations have been made of Scorpius X-1, the Crab Nebula, the low-energy diffuse X-ray background, the Cygnus Loop, and the Perseus cluster. Observations of the Cygnus Loop and the Perseus cluster are in progress and will be reported in the Semiannual Status Reports for NASA grant NGR 33-008-102.

A correlated program in optical astronomy has been carried out. The results of optical observations of X-ray sources are given in Section II.A. Summaries are also included of optical polarization studies of various astronomical objects (Sections II.B.1,2) and of Dr. J. R. P. Angel's work on the circular polarization measurements of white dwarfs (Section II.B.3) which have been supported by the National Science Foundation under grant GP 31356X and by the Research Corporation.

August 1974

DESCRIPTION OF RESEARCH

I. X-RAY ASTRONOMY

A. GENERAL PRINCIPLES OF X-RAY ASTRONOMY

IA1 R. Novick, "Experimental X-Ray Astronomy," in *Atomic Physics and Astrophysics, Brandeis University Summer Institute in Theoretical Physics, 1969*, eds., M. Chrétien and E. Lipworth (Gordon and Breach Science Publishers, New York, N. Y., 1973), Vol. II, pp. 203-283. [CAL No. 29]

The history of X-ray astronomy from 1948 to 1969, its objectives, and the observational techniques which have been used in studying X-ray sources are reviewed. Observations of Sco X-1, the Crab Nebula, and the low-energy diffuse X-ray background are examined and interpreted, and critically needed new developments in X-ray astronomy are discussed.

IA2 J. R. P. Angel, "Polarization of Thermal X-Ray Sources," Astrophys. J. 158, 219-224 (October 1969). [CAL No. 3]

It is shown that radiation from thermal X-ray sources which are not spherically symmetric may show polarization of the order of 1–5% due to Thomson scattering. The polarization mechanism does not depend on this particular nonspherical geometry. More complex models, if one takes into account variable density, temperature, and absorption, would be expected to show polarizarion of the same order of magnitude. The mechanism will also apply to optical bremsstrahlung photons, provided there is not strong absorption, since the classical Thomson cross section is independent of wavelength. Thus, if the contribution from the region of X-ray emission to the total optical output is large, intrinsic optical polarization would be expected.

IA3 J. R. P. Angel, "X-Ray Line Emission from Sco X-1," Nature 224, 160-161 (11 October 1969). [CAL No. 10]

A Monte Carlo technique has been used to obtain an estimate of the spectral distribution of scattered line radiation for a model of Sco X-1. A simple optical model with uniform density having optical depth 12 was examined where photons are generated uniformly throughout the sphere and are scattered with the angular distribution of Thomson theory and without absorption. The

calculation which is valid for the wide range of photon energies for which Thomson scattering holds shows that only 6% of the energy emitted in a given line emerges without any scattering. The remainder is scattered into a broad continuum which would be impossible to detect in the presence of the much stronger bremsstrahlung continuum. If iron lines are found with the strengths predicted for cosmic abundance, then either the plasma is thin in electron scattering or the iron abundance is high. The absence of lines at this strength would be consistent with the high-density models and could not be taken as an indication of synchrotron emission.

IA4 R. Novick, "Galactic X-Ray Polarimetry and High-Resolution X-Ray Spectroscopy," in *X- and Gamma-Ray Astronomy, IAU Symposium 55, Madrid, Spain, 11-13 May 1972*, eds., H. Bradt and R. Giacconi (D. Reidel Publishing Co., Dordrecht, Holland, 1973), pp. 118-131. [CAL No. 67]

Stellar X-ray spectroscopy and polarimetry are discussed in terms of the source parameters that can be determined through such studies and in terms of the constraints that these studies will place on theoretical models. The spectroscopic and polarimetric results that have been obtained to date are reviewed. These include the recent discovery of X-ray polarization in the Crab Nebula and the recent evidence for X-ray coronal line emission in the Cygnus Loop. Finally, the properties and predicted performance of a number of satellite-borne spectrometers and polarimeters are presented.

B. INSTRUMENT DESIGN AND DEVELOPMENT

1. Large-Area Modular X-Ray Focusing System

IB1a F. W. Kantor, R. Novick, and T. E. Wing, "A Large-Area Modular X-Ray Focusing System," in *Proceedings of Symposium on Modern Optics* (Polytechnic Institute of Brooklyn Press, Brooklyn, N. Y., 1967), Vol. 17, pp. 793-799.[1]

[CAL No. 1]

A large-area glancing-reflection X-ray gathering system has been designed and constructed. An intrinsically smooth surface is obtained by using surfaces of gold, vacuum-evaporated onto thin, annealed glass. In two different designs, these coated surfaces are arrayed as parallel-plate modules and nested cones, respectively. There are no critical tolerances in arraying the surfaces. Simple tests on working prototypes have shown that a modular gathering system subtending $>1\text{-m}^2$ input area can easily be built, with $f \simeq 5$ and efficiency $\gtrsim 50\%$ for 10-Å X-rays. This will greatly simplify spectral and polarization measurements on all the known astronomical X-ray sources and provide much more sensitive sky surveys. It will facilitate μ-mesic atom studies by permitting large solid angles to be subtended by small detectors located in a low-background region away from the target. The same approach makes feasible a wide range of crude focusing systems, suitable for photons with energy ranging from 0.1 to about 20,000 eV, which can be of considerable value for improving signal-to-noise ratios in experiments in the vacuum ultraviolet, soft X-ray, and low-energy gamma-ray regions of the electromagnetic spectrum, including possible applications with Mössbauer lines. Glancing angles as small as 1 mrad appear practical; not only photons but also low-energy neutrons can be reflected and focused with angles of incidence this small.

IB1b Frederick B. Kantor, "X-Ray Optics and X-Ray Astronomy," Ph. D. Thesis, Faculty of Pure Science, Columbia University, New York, New York, 1968.[1]

An instrument system, for use in an Aerobee-150 sounding rocket, is described. This instrument is based on a large-area X-ray focusing device. The objective of the experiment is a more

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[1] An experiment was constructed to search for extragalactic sources of X-radiation near the radio galaxy M 87 and the quasar 3C 273 with this instrument. It was integrated and prepared for launch at the White Sands Missile Range in an Aerobee-150 sounding rocket (NASA 4.196 UG) on 2 May 1968. Unfortunately, the rocket failed at launch, and the experiment was completely destroyed.

accurate determination of the location of an X-ray source which has been tentatively associated with the radio galaxy M 87, and a search for a possible X-ray source at the location of the quasar 3C 273. Further applications in X-ray astronomy for instruments based on large X-ray focusing systems are discussed.

2. Incoherent-Scattering Polarimeters

IB2a Thomas E. Wing, "A Polarimeter Suitable for Making Polarization Measurements of Cosmic X-Ray Sources," Ph. D. Thesis, Faculty of Pure Science, Columbia University, New York, New York, 1968.

> A prototype of an incoherent-scattering polarimeter suitable for making polarization measurements of cosmic X-ray sources from an Aerobee-150 rocket has been constructed. Detection of nonzero polarization from a cosmic X-ray source would be strong evidence that the X-rays are generated by synchrotron emission. The prototype polarimeter has been tested in the laboratory and flown from a balloon to investigate the background counting rate at high altitudes. The accuracy to which a polarization measurement can be made is limited by statistical fluctuations in the background and signal counting rates. The polarimeter which will be flown in an Aerobee-150 rocket will be capable of making a measurement of the polarization of Sco X-1 with a standard deviation of 5.5%.

IB2b R. Novick and R. S. Wolff, "A Large-Area Thomson-Scattering Stellar X-Ray Polarimeter," in *New Techniques in Space Astronomy, IAU Symposium 41, Munich, Germany, 10-14 August 1970*, eds., F. Labuhn and R. Lüst (D. Reidel Publishing Co., Dordrecht, Holland, 1971), pp. 159-164. [CAL No. 31]

> An instrument for measuring the polarization of stellar X-ray emission has been designed, constructed, and tested. The polarization dependence of incoherent Thomson scattering in lithium metal is utilized. Means for suppression of cosmic-ray background effects have been provided. The apparatus has been flown in rockets to obtain data on the polarization of X-ray emission from Sco X-1 (Sec. IC1a) and Tau X-1 (Secs. IC2a-c).

IB2c R. S. Wolff, "Balloon-Borne X-Ray Polarimetry," in *Proceedings, Sixth AFCRL Scientific Balloon Symposium*, ed., Lewis A. Grass (U. S. Air Force Cambridge Research Laboratories, L. G. Hanscom Field, Bedford, Mass., 27 October 1970), AFCRL-70-0543, Special Reports No. 105, pp. 3–12. [CAL No. 20]

> An incoherent scattering X-ray polarimeter that has been constructed and successfully flown in sounding rockets for the study of several stellar X-ray sources is described. The application of this instrument from balloon altitudes appears feasible for both stellar and solar experiments when high-altitude, accurately controlled balloons become available.

3. Bragg Crystal Spectrometers and Polarimeters

IB3a J. R. P. Angel and M. C. Weisskopf, "Use of Highly Reflecting Crystals for Spectroscopy and Polarimetry in X-Ray Astronomy," Astron. J. 75, 231-236 (April 1970). [CAL No. 12]

> The way in which Bragg reflection can most efficiently be used for spectroscopy and polarimetry in X-ray astronomy is discussed, and it is shown that both types of measurement are best carried out with crystals of high integrated reflectivity. Graphite, lithium hydride, and tungsten disulfide crystals exhibit this property, provided they have the correct domain structure. Two spectrometers making use of these crystals are described. The first, employing a grazing-incidence lens, combines both very high spectral resolution and high efficiency. The second, simply a plane-reflecting crystal and detector, demonstrates the performance that could be achieved by a small instrument in an OSO satellite. A variety of techniques for using mosaic crystals to measure polarization at the focus of a lens is discussed, and performance is estimated for some possible configurations.

IB3b H. Kestenbaum, J. R. P. Angel, and R. Novick, "A Bragg Spectrometer for Stellar X-Ray Astronomy," in *New Techniques in Space Astronomy, IAU Symposium 41, Munich, Germany, 10-14 August 1970*, eds., F. Labuhn and R. Lüst (D. Reidel Publishing Co., Dordrecht, Holland, 1971), pp. 137-144. [CAL No. 34]

> A Bragg crystal spectrometer is described which was successfully used to scan the spectrum of Sco X-1 in the energy range 2.4–2.9 keV in a sounding rocket experiment (Kitt Peak 3.30) performed on 24 April 1970 (see Sec. IC1b). It consists of two large synthetic graphite crystal panels, each measuring 9 in. × 17 in., mounted on deployable doors of the rocket which open out to 45° when the rocket is above the atmosphere. A scan over a small range of Bragg angles is achieved by changing the attitude of the rocket while the doors remain fully opened. Only X-rays satisfying the Bragg condition are reflected into a central bank of double-sided proportional counters (slat collimators prevent their direct illumination), and the detected pulses are telemetered to ground. Spurious effects are eliminated by making several orthogonal scans across the star which are superimposed by aspect information obtained from photographs of the star field. Temperature is determined in an independent proportional counter experiment mounted on the face of the rocket.

IB3c M. C. Weisskopf, R. Berthelsdorf, G. Epstein, R. Linke, D. Mitchell, R. Novick, and R. S. Wolff, "A Graphite Crystal Polarimeter for Stellar X-Ray Astronomy," Rev. Sci. Instr. 43, 967-976 (July 1972). [CAL No. 52]

The first crystal X-ray polarimeter to be used for X-ray astronomy is described. Polarization is measured by modulation of the X-rays diffracted at an average 45° glancing angle from large, curved graphite crystal panels as these rotate about an axis parallel to the incident X-ray flux. Arrangement of the crystal panels, the design of the detector, and the signal-processing circuitry were optimized to minimize systematic effects produced by off-axis pointing of the rocket and cosmic-ray-induced events. The in-flight performance of the instrument in relation to the observed background signal is discussed.

IB3d A lithium fluoride Bragg crystal spectrometer is described in Secs. IC1f,g.

4. Focusing Collector for Long Wavelength X-Ray Astronomy

IB4a D. Yentis and P. Vanden Bout, "An Instrument for Detecting 44–100-Å Cosmic X-Rays," *1970 Twelfth Scintillation and Semiconductor Counter Symposium, Washington, D. C., 11-13 March 1970*, IEEE Trans. Nucl. Sci. NS-17, 374 (June 1970). [CAL No. 18]

> We have designed, built, and tested an instrument for flight in an Aerobee sounding rocket which will measure the intensity of diffuse cosmic X-rays in the range 44–100-Å while avoiding the systematic problems associated with counter resolution, low-energy cosmic-ray electrons, and ultraviolet radiation. The instrument employs a single reflection off a parabolic mirror to eliminate all high-energy X-rays and soft electrons. The detector is a gas-flow proportional counter with a thin polypropylene window. The window coating and counter design provide a very low ultraviolet sensitivity.

IB4b D. J. Yentis, J. R. P. Angel, D. Mitchell, R. Novick, and P. Vanden Bout, "A Focusing Collector for Long Wavelength X-Ray Astronomy," in *New Techniques in Space Astronomy, IAU Symposium 41, Munich, Germany, 10-14 August 1970*, eds., F. Labuhn and R. Lüst (D. Reidel Publishing Co., Dordrecht, Holland, 1971), pp. 145-158. [CAL No. 35]

> A focusing collector is described in detail which utilizes a grazing incidence paraboloid as an energy concentrator and low-pass filter. The effective bandpass of the instrument from 100 to 280 eV is determined by the combination of the counter window transmission and the mirror reflectivity. The instrument is provided with movable filters, one boron and the other Mylar. The boron filter substantially modifies the bandpass, and the Mylar filter is used to determine the background since it is essentially opaque in the 100–280-eV region. The reflection completely eliminates the problems arising from precipitation electrons and high-energy X-rays. The ultraviolet sensitivity of the instrument is minimized through careful design of the detector and the use of materials with high photoelectric work functions.

C. OBSERVATIONS OF X-RAY SOURCES

1. Scorpius X-1

IC1a J. R. P. Angel, R. Novick, P. Vanden Bout, and R. Wolff, "Search for X-Ray Polarization in Sco X-1," Phys. Rev. Letters 22, 861-865 (21 April 1969). [CAL No. 2]

> A Thomson-scattering X-ray polarimeter, sensitive in the spectral range from 6 to 18 keV, was flown from the White Sands Missile Range on 27 July 1968 in an Aerobee-150 sounding rocket (NASA 4.236 UG). The instrument was used to set an upper limit on the polarization of Sco X-1 and to check for spurious indications of polarization which might result from the anisotropy of the cosmic rays. Within the statistical limitations of the data, no evidence was found for spurious background polarization.

IC1b H. Kestenbaum, J. R. P. Angel, and R. Novick, "X-Ray Spectrum of Scorpius X-1 Obtained with a Bragg Crystal Spectrometer," Astrophys. J. (Letters) 164, L87-L93 (15 March 1971). [CAL No. 38]

> A measurement of the spectrum of Sco X-1 in the range 2.4–2.9 keV shows no emission or absorption features. The measurement was made with a high-resolution Bragg spectrometer (see Sec. IB3b) launched in an Aerobee-170 rocket (Kitt Peak 3.30) from the White Sands Missile Range on 24 April 1970. The Lα line of hydrogenic sulfur at 2.6 keV is found to have an equivalent width $\leq$2.2 eV, a factor 8 less than that predicted for an optically thin plasma at the observed temperature of 8×10^7 °K. The result is explained by a high-density model for the source in which the line is weakened by electron scattering.

IC1c H. Kestenbaum, J. R. P. Angel, R. Novick, and W. J. Cocke, "Correlated Transient Short-Period Oscillation in the Optical and X-Ray Flux from Scorpius X-1," Astrophys. J. (Letters) 169, L49-L55 (15 October 1971). [CAL No. 43]

> A simultaneous observation of the X-ray and optical flux from Sco X-1 was made on 24 April 1970. The X-ray data were obtained with proportional counters flown in an Aerobee-170 rocket (Kitt Peak 3.30), and optical observations were made at the same time at the 90-inch telescope of the Steward Observatory. Correlated oscillations with a 20-sec period have been detected. The oscillations persist for about 2 min and have amplitudes of (0.81 ± 0.17)% and (0.56 ± 0.17)% in the X-ray and optical bands, respectively.

ICld J. R. P. Angel, H. Kestenbaum, and R. Novick, "Evidence of High-Frequency Oscillations in the X-Ray Flux from Scorpius X-1," Astrophys. J. (Letters) 169, L57-L61 (15 October 1971). [CAL No. 44]

> The X-ray flux from Sco X-1, taken over a 4-min period with proportional counters flown in an Aerobee-170 rocket (Kitt Peak 3.30), was analyzed for high frequency structure. Evidence was found for oscillations in the frequency range 1—10 Hz which persist for typically 1 min.

ICle Howard L. Kestenbaum, "Measurement of X-Ray Line Emission from Sco X-1 and Measurement of Temporal Variations in the X-Ray and Optical Flux from Sco X-1," Ph. D. Thesis, Faculty of Pure Science, Columbia University, New York, New York, 1972.

> An experiment employing a large-area, graphite crystal spectrometer was flown aboard an Aerobee-170 sounding rocket (Kitt Peak 3.30) in search of X-ray line emission from the stellar X-ray source Sco X-1. A measurement of the spectrum of Sco X-1 obtained over the range 2.4—2.9 keV showed no emission or absorption features. The Lα line of hydrogenic sulfur at 2.62 keV is found to have an equivalent width $\leq$2.2 eV, a factor of 9 less than that predicted for an optically thin plasma at the observed temperature of 7.5×10^7 °K. The result is explained by a high-density model for the source in which line emission is weakened by electron scattering.
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> A second experiment consisted of proportional counters which monitored the direct flux from Sco X-1 in a search for temporal variations in the X-ray intensity and for correlated activity with the optical flux which was measured simultaneously. Correlated, transient oscillations with a 20-sec period were detected in the X-ray and optical emissions. The oscillations persist for about 2 min and have amplitudes of (0.81 ± 0.17)% and (0.56 ± 0.17)% in the X-ray and optical bands, respectively. An analysis for higher frequency structure of the 4 min of X-ray data obtained during the flight shows evidence for transient oscillatory activity in the frequency range 1—10 Hz. The X-ray oscillations persist for typically 1 min, have amplitudes of about 1%, and often appear with the second harmonic. There is no evidence for persistent periodicity over the entire 4-min X-ray data span, with an upper limit (3-σ) of 0.7% for the amplitude of persistent oscillations in the bandwidth 1—15 Hz.
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> Both experiments, including the design and construction of the instruments, the flight program, the data analysis, and the results, are discussed in detail.

IC1f H. S. Stockman, Jr., J. R. P. Angel, R. Novick, and B. E. Woodgate, "Bragg Spectroscopy of Scorpius X-1 in Search of the Fe XXV Emission Lines," Astrophys. J. (Letters) 183, L63-L66 (15 July 1973). [CAL No. 83]

The X-ray spectrum of Sco X-1 has been measured between 6.73 and 6.65 keV using a large-area LiF Bragg spectrometer. The instrument was flown in an Aerobee-170 sounding rocket (Kitt Peak 3.38) from the White Sands Missile Range on 21 March 1972. The spectrum appears smooth, with no evidence of the Fe XXV emission lines. The results for the equivalent widths of the resonance (6.70 keV), intercombinational (6.68 keV), and forbidden (6.65 keV) lines are 1.1 ± 1.6, -0.1 ± 1.6, and 0.4 ± 2.1 eV, respectively. The lack of line emission at this level places severe restrictions in isothermal models of Sco X-1.

IC1g Hervey S. Stockman, Jr., "Bragg Spectroscopy of Scorpius X-1 in Search of the Fe-XXV Emission Lines," Ph. D. Thesis, Faculty of Pure Science, Columbia University, New York, New York, 1973.

An experiment employing a large-area LiF crystal spectrometer was flown aboard an Aerobee-170 sounding rocket (Kitt Peak 3.38) from the White Sands Missile Range on 21 March 1972 in search of X-ray line emission from the stellar X-ray source Sco X-1. A measurement of the object's spectrum between 6.73 and 6.65 keV shows no evidence of either emission or absorption features. The results for the Fe-XXV resonance (6.70-keV), intercombinational (6.68-keV), and forbidden (6.65-keV) lines' equivalent widths are 1.1 ± 1.6, -0.1 ± 1.6, and 0.4 ± 2.1 eV, respectively. These values are a hundredfold smaller than the predicted line strengths for an optically thin plasma. A plasma model involving source thicknesses of many electron scattering lengths is adopted, and its compatibility with current dynamic models for Sco X-1 is discussed. The instrument, flight program, and the data analysis are described in detail.

2. *The Crab Nebula*

IC2a R. S. Wolff, J. R. P. Angel, R. Novick, and P. Vanden Bout, "Search for Polarization in the X-Ray Emission of the Crab Nebula," Astrophys. J. (Letters) 160, L21-L25 (April 1970). [CAL No. 13]

An incoherent-scattering X-ray polarimeter was constructed and flown in an Aerobee-150 sounding rocket (NASA 4.286) on 7 March 1969 to search for polarization in the X-ray emission of Tau X-1 (the Crab Nebula). The instrument was basically the same as that used by Angel *et al.* (Sec. IC1a) with the addition of pulse rise-time discrimination to reject background counts. Although a result consistent with zero polarization was obtained, the statistics were such that X-ray polarization comparable in magnitude to that of radio or optical emission cannot be excluded.

IC2b Richard S. Wolff, "Measurement of the Polarization of the X-Ray Emission of the Crab Nebula," Ph. D. Thesis, Faculty of Pure Science, Columbia University, New York, New York, 1969.

Detection of polarization in the X-ray emission of a cosmic X-ray source would serve as strong evidence that the X-rays are generated by synchrotron radiation. An X-ray polarimeter to measure the polarization of the X-ray emission of the Crab Nebula has been constructed. The angular dependence of the incoherent scattering cross section on the linear polarization of the incident photon was utilized in the instrument to detect the polarization of the X-ray flux. The instrument, consisting of metallic lithium scattering blocks and xenon-filled proportional counters, was sensitive to photons between 5 and 25 keV. The polarimeter was thoroughly tested and successfully flown in an Aerobee-150 sounding rocket (NASA 4.286) in March 1969 to measure the X-ray polarization of the Crab Nebula. The four minutes of data obtained were analyzed for polarization yielding the results $U/I = -0.050 \pm 0.093$ and $Q/I = 0.072 \pm 0.095$, where U/I and Q/I are the normalized Stokes parameters, or $P = 8.8\%$ with a standard deviation of $\pm 9.5\%$ and $\theta = 163°$. The high background-to-signal ratio and poor counting statistics caused the large uncertainty in the result. The outcome of the experiment was consistent with zero polarization but was also interpreted as setting an upper bound on the probable polarization of the X-ray flux. Our results indicated that the X-ray flux of the Crab Nebula is less than 27% polarized at the 99% statistical confidence level.

IC2c R. Novick, J. R. P. Angel, and R. S. Wolff, "Upper Limit of the X-Ray Polarization of the Crab Nebula," in *The Crab Nebula, IAU Symposium 46, Jodrell Bank, England, 5-7 August 1970*, eds., R. D. Davies and F. G. Smith (D. Reidel Publishing Co., Dordrecht, Holland, 1971), pp. 54-64. [CAL No. 33]

> An incoherent-scattering X-ray polarimeter was flown in an Aerobee-150 sounding rocket (NASA 4.286) on 7 March 1969 to search for polarization in Tau X-1. A schematic representation of the polarimeter concept is given, and the method of data analysis is described. Although a result consistent with zero polarization was obtained, the statistics were such that X-ray polarization comparable in magnitude and direction to that of radio and optical continuum emission cannot be excluded. An upper limit of 27% (at the 99% statistical confidence level) has been set on the polarization of the X-ray emission of Tau X-1.

IC2d R. Novick, M. C. Weisskopf, R. Berthelsdorf, R. Linke, and R. S. Wolff, "Detection of X-Ray Polarization of the Crab Nebula," Astrophys. J. (Letters) 174, L1-L8 (15 May 1972). [CAL No. 56]

> A Bragg crystal polarimeter and a Thomson-scattering polarimeter were launched in an Aerobee-350 sounding rocket (NASA 17.09) from Wallops Island, Virginia, on 22 February 1971 to search for X-ray polarization of the Crab Nebula. The Thomson-scattering polarimeter was a larger version of those described in Secs. IB2b, IC1a, IC2a-c. The graphite crystal polarimeter is described in detail in Sec. IB3c. Polarization was detected at a statistical confidence level of 99.7%. If the X-ray polarization is assumed to be independent of energy, the results of this experiment combined with the data from Sec. IC2a lead to a polarization of (15.4 ± 5.2)% at a position angle of 156° ± 10°. This result confirms the synchrotron model for X-ray emission from the Crab Nebula.

IC2e Richard F. Berthelsdorf, "Measurement of the X-Ray Polarization of the Crab Nebula Using a Crystal Polarimeter," Ph. D. Thesis, Faculty of Pure Science, Columbia University, New York, New York, 1973.

> The X-ray polarization of the Crab Nebula was measured with the first crystal X-ray polarimeter used for X-ray astronomy. The instrument, which made use of the polarization dependence of Bragg reflection, was flown aboard a sounding rocket (NASA 17.09) along with another X-ray polarimeter based on the polarization dependence of Thomson scattering. For the crystal polarimeter alone, the results were a polarization of (24.1 ± 10.2)% at (155 ± 11)° east

of north. Combining the results of the two polarimeters with those of a previous experiment (Sec. IC2a), the X-ray polarization of the Crab Nebula was measured to be (15.4 ± 5.2)% at (156 ± 10)° east of north. These results are in excellent agreement with radio and optical measurements. In addition, the data from the Thomson-scattering polarimeter were analyzed for X-ray pulsing at various periods (see Sec. IC2g). The pulsar in the Crab Nebula (NP 0532) was seen clearly. An upper limit of 2.5×10^{-10} erg $(cm^2\ sec)^{-1}$ between 7 and 18 keV was placed on pulsed X-ray emission from NP 0525 and from the X-ray pulsar reported by D. S. Sadeh *et al.* [Nature 235, 151 (1972)].

IC2f Richard A. Linke, "Measurement of the X-Ray Polarization of the Crab Nebula by Means of a Thomson-Scattering Polarimeter," Ph. D. Thesis, Faculty of Pure Science, Columbia University, New York, New York, 1972.

A Thomson-scattering X-ray polarimeter was employed in the measurement of the linear polarization of the Crab Nebula X-ray emission in an energy range of 7.0 to 17.0 keV. The instrument was flown, together with a Bragg-scattering X-ray polarimeter sensitive from 2.0 to 3.2 keV, in an Aerobee-350 sounding rocket (NASA 17.09) at 1934 UT on 22 February 1971. Polarizations of (14.7 ± 7.9)% and (24.1 ± 10.2)% at angles of (155 ± 14)° and (155 ± 11)° were measured at confidence levels of 82 and 94% by the Thomson- and Bragg-scattering instruments, respectively. The probability of obtaining these results from an unpolarized X-ray flux is shown to be 3%. The agreement between the electric vector position angles measured by the two X-ray polarimeters increases the confidence level of the combined result to 99.7% (3-σ). We consider the possibility of a spurious polarization measurement resulting from systematic instrumental effects and conclude that our result is free from such effects. When these results are combined with those of the previous measurement by Wolff *et al.* (Sec. IC2a), an average Crab Nebula X-ray polarization of (15.4 ± 5.2)% at a position angle of (156 ± 10)° east of north is obtained for an energy range of 2.0 to 22.0 keV. Our result is interpreted as conclusive evidence for applicability of the synchrotron mechanism to the X-ray emission of the Crab Nebula.

IC2g R. Berthelsdorf, R. A. Linke, R. Novick, M. C. Weisskopf, and R. S. Wolff, "X-Ray Observations of Pulsars in the Area of the Crab Nebula," Astrophys. Letters 14, 171-172 (1973). [CAL No. 88]

Data taken with an X-ray polarimeter pointed at the Crab Nebula were analyzed for pulsed phenomena. The Crab pulsar was observed, and the data were searched for periodic pulsation at other frequencies. The pulsed emission from NP 0532 was also analyzed for polarization.

3. Low-Energy Diffuse X-Ray Background

IC3a D. J. Yentis, R. Novick, and P. Vanden Bout, "Positive Detection of an Excess of Low-Energy Diffuse X-Rays at High Galactic Latitude," Astrophys. J. 177, 365-373 (15 October 1972). [CAL No. 48]

> An instrument sensitive to photons in the energy range 0.10—0.28 keV was flown in an Aerobee-170 rocket (NASA 13.01 UG) from the White Sands Missile Range on 14 February 1970 to search for low-energy diffuse X-rays. We have obtained data which confirms the existence of a soft diffuse X-ray flux exceeding in intensity an extrapolation to low energy of the spectrum determined at energies above 1 keV. We show that these data are completely free from contamination by ultraviolet and charged-particle events. To guard against these systematic effects, the rocket payload incorporated X-ray optics and filters (see Secs. IB4a,b). The X-ray spectrum incident at the Earth is shown to be steeply rising at energies less than 0.28 keV, with an integrated energy flux between 0.10 and 0.28 keV of 29.2 keV (sec cm^2 sterad)$^{-1}$.

IC3b D. J. Yentis, R. Novick, and P. Vanden Bout, "Galactic-Latitude Dependence of Low-Energy Diffuse X-Rays," Astrophys. J. 177, 375-386 (15 October 1972). [CAL No. 49]

> A flux of low-energy diffuse X-rays has been observed with a focusing collector (see Secs. IB4a,b) flown in an Aerobee-170 rocket (NASA 13.01 UG) on 14 February 1970. The flux is qualitatively well correlated with 21-cm column densities of hydrogen from intermediate to high galactic latitude. The intensity exceeds that predicted by an extrapolation to low energies of the power-law spectrum observed above 1 keV. The observed X-ray intensity and the apparent correlation with interstellar hydrogen is accounted for by an additional component of extragalactic radiation plus a local component. For the latter, we cannot exclude the possibility that the X-rays are produced in the upper atmosphere. In addition, we have observed a large flux of X-rays near the galactic plane and a prominent feature in the constellation Gemini.

IC3c Daryl Jay Yentis, "Measurement of the Low-Energy Diffuse X-Ray Background," Ph. D. Thesis, Faculty of Pure Science, Columbia University, New York, New York, 1973.

> In a rocket (NASA 13.01 UG) experiment flown on 14 February 1970, data were obtained in the energy range 0.1—0.28 keV which establish the existence of a soft, diffuse X-ray flux exceeding

in intensity an extrapolation to low energy of the power-law spectrum observed above 1 keV. The experiment utilized an X-ray focusing collector and filters to ensure that detected events were due only to soft X-rays and not to ultraviolet radiation or charged particles. The X-ray spectrum incident at the Earth at high galactic latitude (+60°) is found to be steeply rising at energies less than 0.28 keV with an integrated energy flux between 0.1 and 0.28 keV of 29 keV (sec cm^2 sterad)$^{-1}$. Data obtained in a single slow scan of the Galaxy, beginning near the plane in the anticenter direction and ending at galactic latitude +60°, show a qualitative correlation with 21-cm hydrogen data only from intermediate (+30°) to high galactic latitude. To explain the intensity, soft spectrum, and correlation with interstellar hydrogen, both an additional component of extragalactic radiation and a component of very soft galactic radiation are required. For the latter, the possibility that the X-rays are produced in the upper atmosphere cannot be excluded. Some of the excess low-energy radiation can also be explained by a decrease in the opacity of the interstellar medium due to small-scale cloud structure. A large flux of X-rays is observed at low galactic latitude (<+30°). Two prominent features are distinguished. One is very broad in the vicinity of the galactic plane in the Monoceros region of the Galaxy; the other is centered at ℓ^{II} = 199.0°, b^{II} = + 19.3° in the direction of the constellation Gemini. Both features are apparently galactic in origin.

4. Cygnus Loop

IC4a P. Gorenstein, B. Harris, H. Gursky, R. Giacconi, R. Novick, and P. Vanden Bout, "X-Ray Structure of the Cygnus Loop," Science 172, 369-372 (23 April 1971).[1] [CAL No. 36]

> X-ray emission from the Cygnus Loop was observed in the energy region around 0.2–1 keV with a collector launched in an attitude-controlled Aerobee-170 sounding rocket (NASA 13.12 UG) on 26 June 1970 from the White Sands Missile Range. The collector focused X-rays along one dimension while scanning across the nebula. The total integrated intensity is 1.3×10^{-8} erg $(cm^2\ sec)^{-1}$. The one-dimensional X-ray structure has the same angular size — about 3° — as the outermost boundaries of the optical filaments. There is no increase in X-ray emission at the center of the nebula nor at the strong feature that is seen in certain radio maps. The X-ray spectrum is consistent with thermal radiation from a hot plasma at a temperature of about 4×10^6 °K with evidence for a line at 19 Å corresponding to the 2p → 1s transition of O VIII.

IC4b An experiment to observe the low-energy X-ray emission from the Cygnus Loop is scheduled for flight in NASA rocket 13.087 UG on 2 July 1973. Work is being continued, and progress will be reported in the Semiannual Status Reports for NASA grant NGR 33-008-102, entitled "X-Ray Astronomy," which is monitored by the NASA Physics and Astronomy Branch, Code SG, Washington, D. C. 20546.

5. Perseus Cluster

IC5a An experiment to determine the spatial distribution of the X-ray flux of the Perseus cluster is scheduled for flight on 8 February 1974 on NASA rocket 26.021 UG (formerly 13.089 UG). This work is being continued, and the results will be reported in the Semiannual Status Reports for NASA grant NGR 33-008-102.

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[1]Work supported at American Science & Engineering, Cambridge, Mass., under NASA contract NASW-1889.

II. OPTICAL ASTRONOMY

A. OPTICAL OBSERVATIONS OF X-RAY SOURCES

IIA1 D. Hegyi, R. Novick, and P. Thaddeus, "Search for Rapid Fluctuations in Light from the Crab Nebula Pulsar," Astrophys. J. (Letters) 158, L77-L81 (1969). [CAL No. 4]

> Observations have failed to reveal fluctuations in the light from the pulsar NP 0532 on a time scale from about 3×10^{-5} to 1×10^{-8} sec.

IIA2 D. Hegyi, R. Novick, and P. Thaddeus, "A Search for Variations in the Intensity of the Optical Pulses from NP 0532," in *The Crab Nebula, IAU Symposium 46, Jodrell Bank, England, 5-7 August 1970*, eds., R. D. Davies and F. G. Smith (D. Reidel Publishing Co., Dordrecht, Holland, 1971), pp. 129-141. [CAL No. 32]

> A search for short-time variability of NP 0532 using the 82- and 107-inch telescopes at McDonald Observatory is described. Observations were made of the mean intensity, the mean square of the intensity, and the mean autocorrelation function of the pulsar light. Limits are placed on the variability of the optical pulsar.

IIA3 Correlated temporal oscillations in the optical and X-ray flux from Sco X-1 are reported in Secs. IC1c,e.

IIA4 D. W. Kurtz, P. A. Vanden Bout, and J. R. P. Angel, "Search for Coronal Line Emission from the Cygnus Loop, Astrophys. J. 178, 701-706 (15 December 1972). [CAL No. 66]

> The flux from the edges of the Cygnus Loop in the coronal line [Fe XIV]λ5303 is measured to be less than 5×10^{-9} ergs $(cm^2$ sterad $s)^{-1}$ (0.017 R) in a 3 Å band centered on the line. This upper limit is an order of magnitude lower than the predicted total flux in the line and implies that there must be substantial broadening of the line profile by mass motion or that the temperature is somewhat higher than the present best estimate from X-ray data.

B. OPTICAL POLARIZATION STUDIES[1]

1. General[1]

IIB1a J. D. Landstreet and J. R. P. Angel, "Search for Optical Circular Polarization in Quasars and Seyfert Nuclei," Astrophys. J. (Letters) 174, L127-L129 (15 June 1972). [CAL No. 60]

> A search for optical circular polarization has been made in six quasars, the nuclei of three Seyfert galaxies, BL Lac, and OJ 287. With a typical accuracy of 0.1% no positive effect is found in any of these objects, several of which have been reported to show circular polarization at radio wavelengths.

IIB1b P. G. Martin, "Interstellar Circular Polarization," Mon. Not. Roy. Astron. Soc. 159, 179-190 (1972). [CAL No. 62]

> This paper shows that optical observations of circular polarization produced by aligned interstellar grains could yield valuable information about the grain material. The interstellar medium is known to be linearly dichroic from observations of interstellar linear polarization; many different grain models using a large variety of compositions can be found to reproduce these observations. Since the same aligned grains make the medium linearly birefringent, a small component of circular polarization can result from incident linearly polarized light if the position angle of the linear polarization does not coincide with either principal axis of the medium. Here calculations are presented to demonstrate that the wavelength of the circular polarization is sensitive to the imaginary part of the complex refractive index of the grain material. This provides an opportunity of investigating whether the grains are characteristically dielectric or metallic. Some possible observations are suggested.

IIB1c P. G. Martin, R. Illing, and J. R. P. Angel, "Discovery of Interstellar Circular Polarization in the Direction of the Crab Nebula," Mon. Not. Roy. Astron. Soc. 159, 191-201 (1972). [CAL No. 63]

> A search in many small regions of the Crab Nebula has resulted in the detection of a small component of circular polarization. The variation of the sign and magnitude with position in the Nebula indicates that the polarization is of interstellar origin. On the basis of the polarity, strength, and color dependence, it is concluded that the composition of the aligned grains causing this polarization is dielectric. Metallic particles are clearly ruled out. Some stars have also been observed with negative results.

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[1]Work supported by the National Science Foundation under grant GP 31356X and by the Research Corporation; Principal Investigator: J. R. P. Angel, Associate Professor of Physics, Columbia University.

IIB1d J. R. P. Angel, R. Illing, and P. G. Martin, "Circular Polarization of Twilight," Nature 238, 389-390 (18 August 1972). [CAL No. 64]

Circular polarization of twilight of order 10^{-3} has been observed.

IIB1e J. R. P. Angel and P. G. Martin, "Observations of Circumstellar Circular Polarization in Four More Infrared Stars," Astrophys. J. (Letters) 180, L39-L41 (15 February 1973). [CAL No. 85]

Circular polarization at 0.84 μ has been discovered for four stars with characteristics similar to VY CMa and NML Cyg. This polarization is attributed to multiple scattering in an asymmetric circumstellar dust cloud. Some common properties of the class of stars expected to show circumstellar circular polarization are discussed.

IIb1f Rainer M. E. Illing, "Circular Polarization of a Number of Interesting Astronomical Objects," Ph. D. Thesis, Faculty of Pure Science, Columbia University, New York, New York, 1973.

A highly sensitive and accurate polarimeter for circular and linear polarization has been built, employing a fast-switched KD*P crystal as a $\pm\lambda/4$ plate. An extensive discussion of the principles and practices of operation are given. The optical and electronic operation of the system is described, including calibration data and a discussion of possible systematic errors. Two other types of polarimeter are compared to the present instrument.

Observations to find stellar magnetic fields are presented. Data taken on the periodically variable circularly polarized white dwarf G195-19 are examined in detail. Results for three other circularly polarized white dwarfs (Grw+70°8247, G99-37, G99-47) are discussed. A search for magnetic fields in a number of normal stars is presented. The question of circular polarization from the X-ray star Sco X-1 is examined in detail, and data are given which imply that there is no such polarization.

Circular polarization is observed in the light from the Crab Nebula; this implies that the dust cloud through which the Nebula is seen acts as a wave plate. The aligned grains are shown to be primarily of dielectric, and not metallic, composition. Measurements of obscured stars for the same effect are given; no circular polarization is seen. The light of the twilight sky is shown to be partially circularly polarized.

2. X-Ray Sources[1]

IIB2a J. R. P. Angel, D. Hegyi, and J. D. Landstreet, "Measurement of the Circular Polarization of Pulsar NP 0532," in *The Crab Nebula, IAU Symposium 46, Jodrell Bank, England, 5-7 August 1970*, eds., R. D. Davies and F. G. Smith (D. Reidel Publishing Co., Dordrecht, Holland, 1971), pp. 157-159. [CAL No. 27]

> Observations of the optical circular polarization of the pulsar NP 0532 were made on 11/12 February 1970 with a Cassegrain photoelectric polarimeter described in Sec. IIB3a on the 82-inch telescope at McDonald Observatory. The polarization of the whole pulse is not significantly different from zero. Polarization measurements of the leading edge and the trailing edge of the main pulse are also given.

IIB2b J. D. Landstreet and J. R. P. Angel, "Search for Optical Circular Polarization in the Crab Nebula," Nature 230, 103 (12 March 1971). [CAL No. 37]

> A search for optical circular polarization in the Crab Nebula was made on 4/6 November 1970 with the polarimeter described in Sec. IIB3a on the 82-inch telescope at McDonald Observatory. No significant polarization was detected.

IIB2c J. D. Landstreet and J. R. P. Angel, "The Optical Polarization of Scorpius X-1," Astrophys. J. 172, 443-446 (1 March 1972). [CAL No. 45]

> Observations of the wavelength and time dependence of the optical linear polarization of Sco X-1 show that the effect is consistent with an interstellar origin.

IIB2d R. M. E. Illing and P. G. Martin, "Scorpius X-1: A Search for Optical Circular Polarization," Astrophys. J. (Letters) 176, L113-L114 (15 September 1972). [CAL No. 68]

> Upper limits of 0.1% for the circular polarization of Sco X-1 have been obtained in several wavelength bands covering the range 3700–8800 Å.

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[1] See footnote 1, p. 19.

3. White Dwarfs[1]

IIB3a J. R. P. Angel and J. D. Landstreet, "Magnetic Observations of White Dwarfs," Astrophys. J. (Letters) 160, L147-L152 (June 1970). [CAL No. 17]

> A search has been made among the brighter DA-type dwarfs for magnetic fields by using a new, highly sensitive photoelectric polarimeter. No magnetic fields have been detected in the nine stars so far observed, and upper limits of about 10^5 gauss can be placed on fields that may be present.

IIB3b J. C. Kemp, J. B. Swedlund, J. D. Landstreet, and J. R. P. Angel, "Discovery of Circularly Polarized Light from a White Dwarf," Astrophys. J. (Letters) 161, L77-L79 (August 1970). [CAL No. 23]

> Strong circular polarization, 1—3%, has been discovered in visible light from the semi-DC "peculiar" white dwarf Grw+70°-8247. This is the first such observation on any white dwarf, and is taken as indicating a strong magnetic field. From the theory of gray-body magnetoemissivity, to which the wavelength dependence of the circular polarization would appear to conform, one estimates a mean projected B field of 1×10^7 gauss.

IIB3c J. R. P. Angel and J. D. Landstreet, "Further Polarization Studies of Grw+70°8247 and Other White Dwarfs," Astrophys. J. (Letters) 162, L61-L66 (October 1970). [CAL No. 26]

> Further observations of polarization in the white dwarf Grw+70°-8247 have been made. The circular polarization in a broad band from 4000 to 6000 Å is found not to fluctuate by more than 3% on a time scale from 24 sec to a few days. The circular polarization rises steeply from less than 1% at 3300 Å to 3.5% at 4000 Å, and then drops slowly to 2.5% at 7600 Å. In ultraviolet and blue light the star shows a component of linear polarization of between 2 and 3.5% at a position angle of about 20°.
>
> Six other DC white dwarfs, one DA and one DBp, examined for circular polarization, gave null results generally to an accuracy of about 0.1%.

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[1] See footnote 1, p. 19.

IIB3d J. D. Landstreet and J. R. P. Angel, "Magnetism in White Dwarfs," in *The Crab Nebula, IAU Symposium 46, Jodrell Bank, England, 5-7 August 1970*, eds., R. D. Davies and F. G. Smith (D. Reidel Publishing Co., Dordrecht, Holland, 1971), pp. 234-236. [CAL No. 30]

Searches have been made for the normal and quadratic Zeeman effect and broad-band circular polarization in white dwarf stars. A positive effect has been found in Grw+70°8247 whose continuum shows both linear and circular polarization.

IIB3e J. R. P. Angel and J. D. Landstreet, "The Polarization of Radiation from White Dwarfs," in *White Dwarfs, IAU Symposium 42, St. Andrews, Fife, Scotland, 11-13 August 1970*, ed., W. J. Luyten (D. Reidel Publishing Co., Dordrecht, Holland, 1971), pp. 79-80. [CAL No. 35A]

The circular polarization in the white dwarf Grw+70°8247 measured in a broad band from 4000 to 7000 Å is found not to vary from its mean value by more than 3% on any time scale from 24 sec to 2 weeks. The circular polarization rises sharply from about 0.75% at 3300 Å to a maximum of 3.7% at 4100 Å, and then decreases smoothly to about 1.3% at 9400 Å. Blueward of 6400 Å the position angle of linear polarization is about 20°, while at two measured red points at 8200 Å and 9400 Å, it is respectively 101° and 148°.

A search for circular polarization in 6 DC stars, one DA, and the peculiar DB star HZ29 has not resulted in the discovery of any other circularly polarized white dwarfs.

IIB3f J. R. P. Angel and J. D. Landstreet, "Detection of Circular Polarization in a Second White Dwarf," Astrophys. J. (Letters) 164, L15-L16 (15 February 1971). [CAL No. 39]

The continuum radiation in a band from 3800 to 6000 Å from the white dwarf G195-19 is found to have circular polarization of $(0.42 \pm 0.04)\%$.

IIB3g J. D. Landstreet and J. R. P. Angel, "Discovery of Circular Polarization in the White Dwarf G99-37," Astrophys. J. (Letters) 165, L67-L70 (1 May 1971). [CAL No. 40]

The continuum radiation in a band from 3800 to 6000 Å from the DGp white dwarf G99-37 is found to have circular polarization of (0.63 ± 0.03)%. The effect in this band does not appear to be time variable, although variations of about 0.3% may be present in narrower wavelength bands. The polarization drops from 0.98% in the ultraviolet to 0.44% in the blue and then rises gradually to a value around 0.8% in the red. A search for linear polarization did not show a definite effect, the measured value in a broad band being p = (0.21 ± 0.13)%.

A list is given of 24 other stars which have been observed for circular polarization with negative results.

IIB3h J. R. P. Angel and J. D. Landstreet, "Discovery of Periodic Variations in the Circular Polarization of the White Dwarf G195-19," Astrophys. J. (Letters) 165, L71-L75 (1 May 1971). [CAL No. 41]

The circular polarization observed in the continuum radiation of the DC white dwarf G195-19 has been found to be periodically variable with a period of 1.34 days. In the wavelength band 3800-5400 Å, the mean polarization is -0.224% and the amplitude of the variable component is 0.250%. The polarization in other bands is not so strongly modulated. In a broad wavelength band the star showed no detectable linear polarization, (0.09 ± 0.13)%, at a time when the circular polarization was close to maximum.

IIB3i J. R. P. Angel, J. D. Landstreet, and J. B. Oke, "The Spectral Dependence of Circular Polarization in Grw+70°8247," Astrophys. J. (Letters) 171, L11-L15 (1 January 1972). [CAL No. 53]

Sharp changes in circular polarization with wavelength are seen in new observations of Grw+70°8247 made with 80-Å resolution. Some of the structure is associated with the Minkowski bands. Continued broad-band measurements show that while the polarization below 6000 Å appears to remain constant, above this wavelength there have been significant changes in the past year.

IIB3j J. R. P. Angel, "Interpretation of the Minkowski Bands in Grw+70°8247," Astrophys. J. (Letters) 171, L17-L21 (1 January 1972). [CAL No. 54]

It is argued from the spectral structure of circular polarization in Grw+70°8247 that the absorption bands are at least in part molecular in origin. The spectrum of molecular helium has

strong bands coincident with several of the Minkowski bands and, in particular, at high temperature shows a strong band head at ~4125 Å. Helium molecules could be formed in sufficient density to give the absorption features in the star if it has a pure helium atmosphere. The Zeeman effect in molecular helium can explain in general the observed spectral features in the polarization and also may be responsible for the continuum polarization.

IIB3k J. R. P. Angel, R. M. E. Illing, and J. D. Landstreet, "New Measurements of Circular Polarization and an Ephemeris for the Variable White Dwarf G195-19," Astrophys. J. (Letters) 175, L85-L87 (15 July 1972). [CAL No. 46]

Observations of the white dwarf G195-19 made for over a year show that the periodic variation in circular polarization continues with constant frequency and amplitude; an accurate value for the period, 1.3309 ± 0.0004 days, is obtained. While the variation in blue-green light is sinusoidal, extensive measurements in red light show an asymmetric curve, reaching a minimum about 6 hours earlier than in the blue-green.

IIB31 J. R. P. Angel and J. D. Landstreet, "Discovery of Circular Polarization in the Red Degenerate Star G99-47," Astrophys. J. (Letters) 178, L21-L22 (15 November 1972). [CAL No. 73]

Circular polarization is found in the light of the cool DC white dwarf G99-47 = GR 289, varying from 0.45% in the ultraviolet to 0.30% in the near-infrared. No evidence for time variability of the polarization is found.

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