10. GALACTIC X-RAY POLARIMETRY AND HIGH-RESOLUTION X-RAY SPECTROSCOPY

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Abstract. 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.

1. Introduction

While very great progress has been made in X-ray astronomy with very simple observational tools, it is clear that the further development of the subject requires high-resolution spectroscopic and polarimetric observations. The photometric methods that have been used have served to reveal the binary nature of a number of compact X-ray sources. Modulation collimator and lunar occultation data have provided very precise positional data. In a number of cases it has been possible to correlate X-ray sources with particular radio and optical objects. Such correlations have enormously expanded our knowledge of these sources and have yielded some important optical spectroscopic observations on a few of them. Since the X-ray, optical, and radio emission regions may not be identical in the various sources, it is clear that direct X-ray spectroscopic and polarimetric observations must be made if we are to understand the physical conditions in the X-ray emitting regions. Also, since some objects seem to have no observable optical counterpart, we must rely entirely on X-ray observations to understand these objects. Thus it is clear that spectroscopic and polarimetric observations are essential for determining the physical conditions in the X-ray sources and for distinguishing between various theoretical models.

In this review we indicate the nature of the information that we hope to obtain about X-ray sources through spectroscopic and polarimetric observations. We discuss instrumental problems, we indicate the present satellite flight schedule for various spectrometers and polarimeters, and finally we review the results that have been obtained to date.

2. Spectroscopy

Spectral lines will be observable in all thermal X-ray sources. Knowledge of the width of these lines, their intensities, and possible shifts will be essential for the determination of the temperature, density, abundances, mass motions, and gravitational fields within the emitting region. The spectroscopic techniques that are available include the

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use of proportional counters, solid-state detectors, filters, gratings, and Bragg crystal spectrometers.

Proportional counters are available with large areas and with low background counting rates. Their energy resolution is limited by the relatively high effective ionization energy of the counting gas. Typically 30 eV are required to produce an ion pair in the gas, and this implies a resolution width of 170 eV at 1 keV photon energy.

The most comprehensive development on proportional counters has been accomplished by Boldt and his collaborators of the NASA Goddard Space Flight Center. This group has pioneered in the development of multiwire, multidepth proportional counters in which they have achieved a resolution of 840 eV with the 6-keV ^{55}Fe X-ray line (Bleach *et al.*, 1972). At longer wavelengths, a resolution of 190 eV has been reported for the 282-eV carbon-K line and 170 eV at the 185-eV boron-K line with simple proportional counters operating with pure methane gas (Yentis *et al.*, 1971).

Solid-state detectors require only a few electron volts per ion pair and therefore exhibit much higher resolution than proportional counters. Goulding and Stone (1970) have reviewed the status of the development of solid-state X-ray detectors. At low photon energies, the resolution is limited by preamplifier noise, and the best reported resolution at long wavelengths is 105 eV (Landis *et al.*, 1970). Unfortunately, it seems to be difficult to produce large-area, high-resolution solid-state detectors, and in addition they must be refrigerated to obtain the best resolution. In view of their small size it appears that solid-state detectors can best be used in conjunction with focusing optics. Very dramatic improvements could be made in X-ray astronomy if large-area, high-resolution, position-sensitive solid-state detectors could be developed. Among other applications, such a detector could be used at the focus of a true X-ray telescope to serve as an image-forming element with reasonable spectral resolution. One advantage of these detectors over proportional counters for this application is the fact that the detectors are relatively thin; they therefore could be used with very high-resolution telescopes which have a limited depth of focus. This application would require spatial resolution on the order of 0.02 mm.

In May, 1971, Singer (1972), of the Los Alamos Scientific Laboratory, flew three lithium-drifted silicon detectors in a rocket designed to study the spectrum of Sco X-1. Each detector had an area of 1.1 cm^2, they were cooled with liquid nitrogen, and the resolution widths, determined by electronic noise, were about 250 eV. One detector provided background information. While the final results have not been published, Singer finds that the energy spectrum is flat from about 700 eV to 4 keV with a constant intensity (within 20%) of 25 ± 5 keV keV^{-1} cm^{-2} s^{-1}. At higher energy, the spectrum falls according to the well-known thermal bremsstrahlung formula with a temperature in the range of about 3 keV. Singer finds no evidence for any lines, but the area of his detector is so small that even with the improved resolution, he would not have been able to detect the 7-keV feature suggested by proportional counter experiments (see below). Singer has stated that his data suggest the presence of an absorption feature at the neon absorption edge, but the statistical significance of this feature is not clear.

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Womack and Overbeck (1972), of the Massachusetts Institute of Technology, have also flown a solid-state detector in a balloon, but their results have not yet been published. The X-ray astronomy group of the NASA Goddard Space Flight Center is scheduled to fly a cooled nonimaging solid-state detector at the focal plane of the high-efficiency telescope in the HEAO-C spacecraft.

The theoretical resolution ($\lambda/\Delta\lambda$) of gratings is equal to the total number of lines in the grating. In practice, the resolution is determined by the width of the entrance and exit slits and by aberrations. Various groups are working on true astigmatic focusing holographic gratings of sufficient size to be useful for nonsolar X-ray astronomy (Pieuchard *et al.*, 1972). Diffraction gratings were successfully used to study the solar corona in the far ultraviolet during the March, 1970, solar eclipse (Speer *et al.*, 1970). The American Science & Engineering (AS&E) X-ray astronomy group is scheduled to fly a normal incidence transmission objective grating on the HEAO-C spacecraft. It is expected that the resolution ($\lambda/\Delta\lambda$) of this grating will be about 50.

True Bragg crystal spectrometers offer a very great promise in stellar X-ray astronomy. In view of the low fluxes from most sources, it is necessary to employ crystal areas of several thousand square centimeters or more. The X-ray astronomy groups at the University of Leicester, at the Los Alamos Scientific Laboratory, and at the Columbia Astrophysics Laboratory have flown large-area spectrometers in sounding rockets to search for the Fe XXV, the S XVI, the Ne IX, and the O VIII lines in Sco X-1.

In the first Leicester flight on March 18, 1970, a lithium fluoride spectrometer with an effective crystal area of 220 cm^2 was used to search for the ($1s^2\,{}^1S$–$1s2p\,{}^1P$) line of Fe XXV (6.70 keV) in the X-ray spectrum of Sco X-1 (Griffiths *et al.*, 1971). No line was detected, and an upper limit (at the 3-σ level of confidence) of 1.2×10^{-9} ergs cm^{-2} s^{-1} was established on narrow-line emission from Sco X-1 between 1.83 Å and 1.91 Å. The overall spectrum between 4 and 14 keV was observed with a proportional counter, and it was found that the electron temperature was 6×10^7 K. By combining this result with the above limit on the line flux, it was found that the 3–σ upper limit on the equivalent width of any narrow line between 6.51 and 6.77 keV was 50 eV. The alignment of the crystals of this spectrometer was improved so that the width of the rocking curve was reduced from 10′ to 5′. This improved spectrometer was flown on March 11, 1971, in another search for the Fe XXV lines in Sco X-1. Again, no lines were observed, and the 3-σ limit on narrow-line emission from Fe XXV was reduced to an equivalent width of 25 eV when the source temperature was 5.5×10^7 K (Griffiths, 1972).

The Los Alamos Scientific Laboratory flew mica and KAP crystal spectrometers in a rocket to search for the Ne IX and O VIII lines in Sco X-1. Each spectrometer employed two crystal panels each with an area of about 290 cm^2. The continuum from Sco X-1 was observed with each spectrometer, but no lines were observed. The authors have not given upper limits on either the line strengths or the equivalent widths of these lines (Argo *et al.*, 1972).

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On April 24, 1970, the Columbia Astrophysics Laboratory flew a 2000-cm^2 graphite crystal spectrometer in an Aerobee-170 rocket to search for the S XVI line in Sco X-1 (Kestenbaum *et al.*, 1971). Again, the continuum was detected with a temperature of 8×10^7 K, but no line was observed. The 3-σ upper limits on line strength and equivalent width were 0.08 photons cm^{-2} s^{-1} and 6.7 eV, respectively. In a more recent Aerobee-170 rocket flight on March 22, 1972, a lithium-fluoride spectrometer with 3400-cm^2 crystal area was flown to search for the Fe XXV lines in Sco X-1. No lines were observed, and it was shown that at the 3-σ level the equivalent width of the Fe XXV lines was 3 eV or less (Stockman *et al.*, 1972).

It is generally agreed that the absence of sharp lines in Sco X-1 results from severe broadening in this dense object. The first estimate of these effects was made by Angel (1969a) who showed that at a temperature of 5×10^7 K and a density of 10^{16} electrons cm^{-3}, suggested by the infrared observations, the line strengths will be decreased by a factor of about 16 by electron scattering. These calculations have been considerably refined and extended by Loh and Garmire (1971) and by Felten *et al.*, (1972). These authors include the effects of photoionization by the intense X-ray flux in Sco X-1 and the effect of trapping on the resonance lines. They show that at a temperature of 7×10^7 K and an optical depth of 5 for electron scattering, the equivalent width of the core of the S XVI Lα line of 2.62 keV is 0.32 eV. In the case of the Fe XXV resonance line at a temperature of 5×10^7 K and an optical depth for scattering of 5, the predicted equivalent width of the line core is 1.9 eV. Under the same conditions, the sum of the equivalent widths of the Fe XXV forbidden and intercombination lines is predicted to be 34 eV. Thus, the observations indicate that either the temperature or the density is higher than the values assumed above. For example, according to Felten *et al.* (1972), if the temperature were 7×10^7 K and the optical depth were 10, then the predicted equivalent width of the Fe XXV resonance and intercombination lines would be about 3 eV, consistent with the observations. Alternatively, the temperature and density may have lower values suggested above, but there may be appreciable mass motion and turbulence in the source. Such motion would, of course, broaden the line core remaining after scattering. Mass motion is expected if the radiation arises in an accretion disk surrounding a dense stellar object. In any case it is clear that any further observations of Sco X-1 require long-term satellite observations. As an example of the power of satellite spectrometers, we note that the Bragg crystal spectrometer on HEAO-B (see below) will have sufficient sensitivity to detect the Fe XXV and Fe XXVI lines in Sco X-1 in one day at the 3-σ level if the equivalent width of the core is 0.2 eV or more. In addition, this spectrometer will have sufficient sensitivity to reveal the O VII coronal lines in Alpha Centauri at the 3-σ level in five days if they have the same strength as those observed on the Sun. The detection of the lines in Sco X-1 and other compact sources is essential for determining the density, temperature, and velocity distribution in the X-ray emitting region.

In addition to the Bragg crystal and solid-state detector studies of Sco X-1 discussed above, numerous observations have been made of this object with proportional counters. Four groups report weak, broad features in the neighborhood of the 7-keV

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iron lines. The U.S. Naval Research Laboratory reports a 3-σ upper limit on iron line emission from Sco X-1 with an equivalent width of about 50 eV at a temperature of 5.5×10^7 K (Meekins *et al.*, 1969). The NASA Goddard Space Flight Center reported a 3.25-σ iron line feature with an equivalent width of about 50 eV and a temperature of 6×10^7 K (Holt *et al.*, 1969, 1970). The University of Leicester reported a 5-σ upper limit on the iron line with an equivalent width of 100 eV at a temperature of 5.5×10^7 K (Griffiths, 1972). The Lockheed group reported an observation of iron line emission with an equivalent width of 240 ± 140 eV at a temperature of 5.5×10^7 K (Acton *et al.*, 1970). In the case of the Lockheed experiment, it should be noted that the detector used had a very thick window that caused considerable curvature in the observed spectrum at the position of the iron line. Ignoring the Lockheed result, we find that the equivalent width of the iron lines in Sco X-1 as observed with proportional counters is 100 eV or less. Since the resolution width of a proportional counter of 7 keV is about 1 keV, these results cannot be directly compared with the estimates of Felten *et al.* (1972). As noted above, these authors estimated the equivalent width of the cores of the Fe XXV and S XVI lines as well as the equivalent width of the total line. Since the total line energy is spread over several keV (Angel, 1969a), it will be necessary to make detailed predictions of the line shape before making a comparison with theory. As yet no detailed line-shape or continuum-shape predictions have been made for compact X-ray sources.

The HEAO-B satellite will contain two stellar Bragg crystal X-ray spectrometers, one to cover the 1 to 8 keV region and the other to cover the 0.4 to 2 keV region. This will be the first satellite-borne spectrometer to observe the region below 1 keV. The higher-energy spectrometer will contain flat crystals for high resolution such as germanium with subarc-minute rocking curves and crystals for high integrated reflectivity such as graphite to observe broad lines and the detailed shape of continua. Mounted on the back of the high-energy crystal panel will be another crystal such as PET. The panel can be rotated to expose either the PET or the germanium and graphite crystals. The lower-energy spectrometer will use flat crystals of RAP and a thin window counter as detector. It is hoped to collect the radiation reflected by the crystal in paraboloidal mirrors and to focus the radiation into very small detectors in order to reduce the background rate. It is also hoped to put an array of grazing-incidence gratings back to back to the RAP to be able to observe in the energy range 0.1 to 0.5 keV. The area of each crystal panel will be 2300 cm^2. The orientation of both the crystal panels and the detectors can be controlled in orbit in order to perform a Bragg scan. Sources can be observed for several days if necessary.

In addition to HEAO-B, the OSO-I, ANS, UK-5, and the HEAO-C spacecraft will also contain stellar Bragg crystal X-ray spectrometers. The OSO-I instrument will contain a large-area mosaic crystal spectrometer that will be useful for determining the exact shape of the continua from a number of sources, and in addition, it will provide a complete spectral survey of all of the presently known sources. The OSO-I spectrometer consists of two 970-cm^2 graphite crystal panels that view the X-ray sky through the edge of the satellite wheel compartment. The angle between the panels is

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40° and located between them is a two-sided proportional counter. The Bragg scan from 9° to 84° (11.8 to 1.86 keV) is accomplished by the rotation of the satellite wheel compartment.

The ANS instrument consists of two 65-cm^2 EDDT or PET crystal panels oriented at about 45° to the viewing direction. One crystal is adjusted to detect the Si XIII lines and the other the Si XIV line. The spacecraft can be oriented so that a source can be studied for about one-half day. The UK-5 spectrometer will employ graphite and lithium hydride crystal panels. Each panel has an area of about 200 cm^2. The Bragg angle is adjustable in flight from 25° to 65° and can be set at 45° for polarimetry (see below). The spectral range of the instrument extends from 2 to 8 keV. The viewing direction of the spectrometer is parallel to the spacecraft spin axis so that sources may be observed for extended periods of time. The HEAO-C spectrometers employ very high-resolution, curved crystals at the focus of the high-resolution (1″) telescope. These instruments will permit detailed studies of the line shapes and shifts.

Angel and Weisskopf (1970) have proposed and tested a novel Bragg objective crystal spectrometer that appears to have a great promise. Briefly, the instrument consists of a large-area crystal mounted in front of an X-ray telescope. The angle between the telescope axis and the crystal plane and the angle between the crystal plane and the line of sight to the X-ray star are chosen to satisfy the Bragg condition for a particular X-ray line or multiplet. A spectral line appears in the focal plane of the telescope as an arc of a large diameter circle. The resolution of the instrument is determined by the diffraction width of the individual domains in the crystal panel, and the spectral range is determined by the mosaic spread in the crystal and the field of view of the telescope. Since the entire aperture of the telescope can be illuminated by the diffracted beam, the instrument has very high sensitivity. A schematic diagram of this spectrometer is shown in Figure 1, and in Figure 2 we show the rhodium $L\alpha_1$ and $L\alpha_2$ lines as observed in the laboratory with a small grazing incidence telescope and an objective mosaic graphite crystal. The 3.5-eV linewidth observed here is determined by the natural width of the rhodium lines and is in excellent agreement with the 2.75-eV width obtained with a very high-quality calcite Bragg crystal spectrometer. The energy and Bragg-angle separation of the $L\alpha_1$ and $L\alpha_2$ lines are 4.69 eV and 5.5′, respectively. The mosaic spread of the crystal used in this experiment was 24′. The fact that the $L\alpha_1$ and $L\alpha_2$ lines could be clearly resolved shows that the resolution of the objective crystal spectrometer is determined by the diffraction width of the individual domains rather than the mosaic spread of the crystal.

The only object besides Sco X-1 which has been subject to detailed spectroscopic study is the Cygnus Loop. It is believed that this is a supernova remnant and that the emitting region is a low-density, high-temperature plasma. If this is correct, then coronal lines should be observable in both the X-ray and visible bands. In a collaborative experiment between AS & E and Columbia, the Cygnus Loop was observed with a one-dimensional focusing collector and thin window proportional counter (Gorenstein *et al.*, 1971). The data rule out a power-law spectrum and strongly suggest a thermal bremsstrahlung spectrum with $T = 4.3 \times 10^6$ K and a line at 0.65 keV in the

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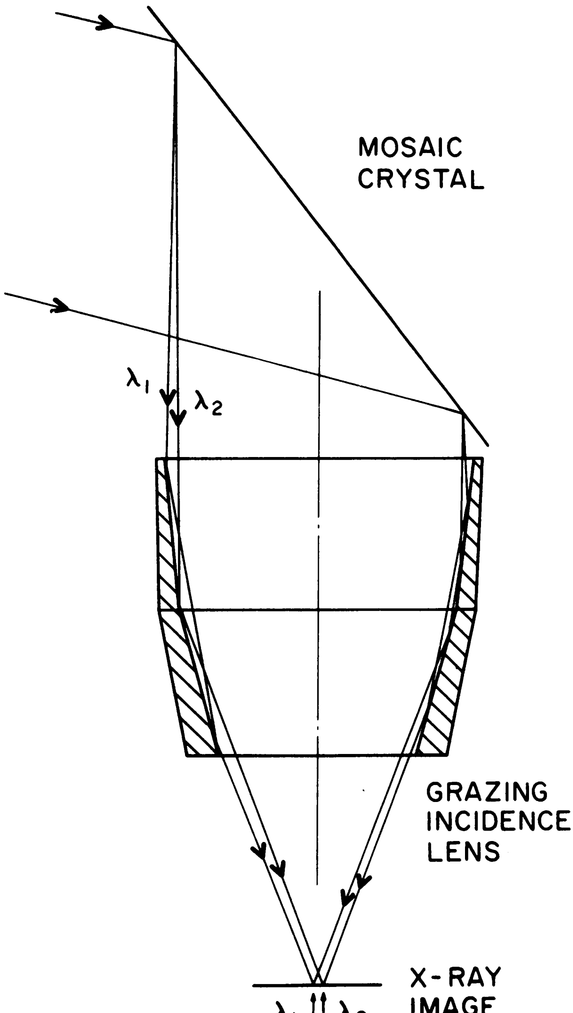

Fig. 1. Schematic diagram of the Bragg objective crystal spectrometer.

neighborhood of the expected coronal O VII and O VIII lines. Tucker (1971) reinterpreted these data and suggested that the temperature might be 2×10^6 K. The interpretation of the line depends on our knowledge of the reflection efficiency of the focusing collector since this instrument employed a chromium surface which has a strong absorption feature close to the oxygen lines. The reflection efficiency of the mirror was measured at 10 Å and 44 Å and found to be in good agreement with the results of Ershov *et al.* (1967). Thus there was no reason to believe that the assumed reflection efficiency in the neighborhood of 0.65 keV is incorrect. Recently Bleeker *et al.* (1972) reported on a very careful proportional counter study of the Cygnus Loop. They confirmed the thermal spectrum with $T = 2.7 \times 10^6$ K but found that they were

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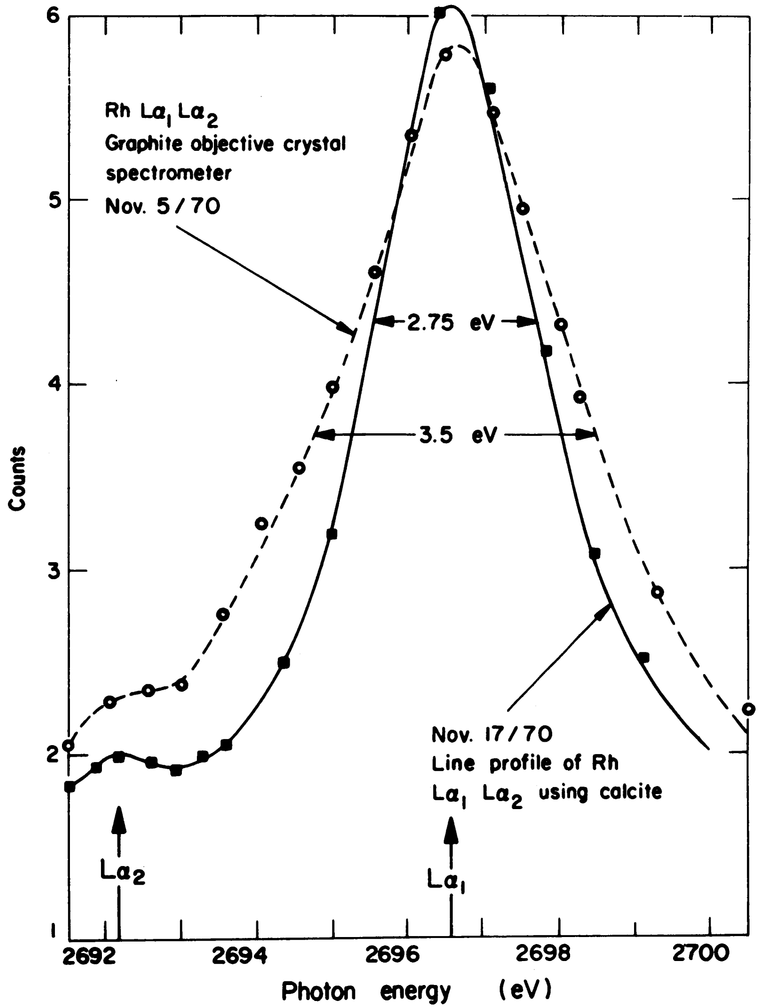

Fig. 2. Rhodium Lα_1 and Lα_2 lines observed with a small mosaic graphite objective crystal spectrometer and with a conventional high-resolution calcite crystal spectrometer.

not required to assume the existence of X-ray lines to fit their data. More recently, Stevens *et al.* (1972) made a study of this object with proportional counters and balanced absorption filters. One of the filters consisted of a gas cell that was filled with oxygen during the rocket flight. The other was a thin Teflon sheet that provided the fluorine absorption edge. This experiment has provided very strong evidence for the existence of the oxygen lines. Thus, it appears that the Cygnus Loop is the first non-solar object to exhibit X-ray lines.

Kurtz *et al.* (1972) have made extensive searches for the optical coronal Fe XIV line at 5303 Å in the Cygnus Loop, but so far they have failed to detect the lines. Using a filter with 3-Å bandwidth, they have shown that the λ5303 flux from the Cygnus

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Loop is less than 5×10^{-9} ergs cm^{-2} $sterad^{-1}$ s^{-1}. This is an order of magnitude less than the predicted total flux for a plasma temperature of 2.7×10^6 K. This negative result is taken to indicate either broadening of the line profile by mass motion or a higher temperature in the Loop. Clearly, it is essential not only to detect the X-ray and optical lines but also to determine their intensity and profile. This information will provide a direct measure of the temperature and velocity distribution within the Loop and will certainly help to clarify the difference between the 110 km s^{-1} velocity observed in the filaments and the 430 km s^{-1} shock velocity required by the X-ray observations (Woltjer, 1972).

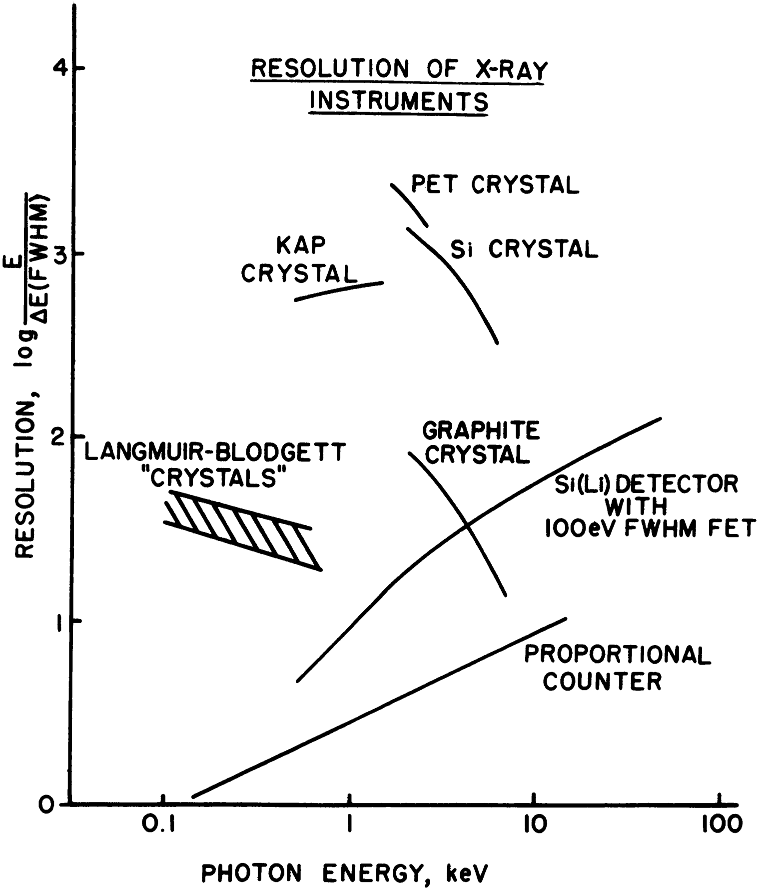

Fig. 3. Resolution of X-ray instruments.

In this section we have indicated the present status of X-ray spectroscopy, particularly in regard to Sco X-1 and the Cygnus Loop. Also, we have indicated the instrumental developments, and we have briefly indicated the forthcoming satellite X-ray spectroscopy experiments. In Figure 3, we briefly summarize the resolution of various types of spectrometers.

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3. Polarimetry

X-ray polarization is expected in any source that is either nonthermal or aspherical. In the case of synchrotron emission, it is well known that linear polarization is observed, that it is independent of energy, and that the polarization pattern within an extended source provides a map of the magnetic field. In the case of a dense aspherical thermal source, polarization of a few percent is expected if there is strong scattering within the source (Angel, 1969b). Recently Pringle and Rees (1972) suggested a model for the pulsating binary X-ray source Cen X-3 in which the emission results from the accretion of matter onto the poles of a rotating magnetic neutron star. If the model is correct, it is expected that the source will exhibit both linear and circular polarization and that the polarization will depend upon the X-ray pulse phase. In this review we will primarily discuss linear polarization, but we note in passing that X-ray circular polarization has been detected by observing the Compton scattering of photons by the polarized *d* shell electrons in magnetized iron (Goldhaber *et al.*, 1958).

It is, of course, well known that the Crab pulsar NP 0532 exhibits phase-dependent linear polarization in both the radio and optical bands, and it is expected that X-ray polarization will also be observed in this object. In the exploding galaxy M 87, it is known that polarization up to 20% exists in the visible band in some of the 'knots' in the jet. This fact is taken as evidence of synchrotron emission (Hiltner, 1959). If the X-ray emission occurs by the same process, then we might expect similar polarization. Since the average polarization for the entire galaxy is much lower than the above amount, we can only expect to observe polarization with a nonimaging polarimeter if the X-ray emission is primarily confined to one or two 'knots'. One of the favorite models for the compact X-ray source Sco X-1 ascribes the X-ray emission to a high-temperature accretion disk that surrounds a white dwarf member of a contact binary star system. As yet no evidence has been found for binary motion in this source. If the accretion model is correct, then we might expect a few percent X-ray polarization (Angel, 1969b) due to scattering within the disk. Thus, polarimetry may be useful for establishing the true nature of this and other compact X-ray sources.

Finally, it is noted that, in the impact of monodirectional electrons onto matter, linear polarization is observed and that the sign and magnitude of the polarization depend on the photon energy. At low photon energies, the polarization (electric vector) is perpendicular to the direction of electron flow. At photon energies near the upper end of the bremsstrahlung spectrum, the polarization is parallel to the electron flow. This process is known as linear bremsstrahlung and is believed to account for the X-ray polarization observed by Tindo *et al.* (1971) in solar flares. It is conceivable that a similar process occurs in the flares observed in Sco X-1 and the other highly variable X-ray sources. In this case it is critical to observe the energy dependence of the polarization with a broad-band polarimeter. It is amusing to speculate that the high-energy nonthermal spectral 'tail' observed in Sco X-1 at energies above 40 keV may be produced by the synchrotron process and may exhibit strong polarization. It is clear from the above discussion that polarimetry is essential for the determination

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of both the structure and X-ray emission mechanisms in a number of X-ray sources.

The techniques that have been used for X-ray polarimetry depend on the angular asymmetry of electron scattering. If the electrons are essentially free (i.e., their binding is small compared to the photon energy), then scattering is observed over a broad energy band, and it has a characteristic dipole form with the axis of the dipole co-aligned with the polarization (electric vector) of the incident polarized photon. If the electrons are bound in a regular crystal lattice, than the scattering (Bragg reflection in this case) is restricted to a narrow energy band given by the mosaic spread of the crystal. The scattering observed with a Bragg angle of 45° is zero if the polarization vector is in the plane of incidence, and it is maximum if it is perpendicular to this plane. In principle, other techniques can be used for polarimetry, but so far none of them have proved as effective as the scattering method. The technique most often considered involves detecting the direction of the primary photoelectron track. Unfortunately, at the energy at which most X-ray sources are most intense (1–20 keV), it is very difficult to detect the direction of an electron track. At energies of 50 keV and higher, this method is probably superior to the scattering method. At much higher energies it will probably be best to determine polarization from the orientation of the plane of the electron pairs formed by a converter in a spark chamber.

All of the X-ray polarization studies that have been made to date have used either Thomson scattering in lithium or beryllium or Bragg reflection at 45° on mosaic graphite crystals. Mosaic graphite is used for polarimetry since it has the highest integrated reflectivity at an energy (2.6 keV) near the maximum in the spectrum of most X-ray sources. The Thomson-scattering polarimeters provide data over a broad band, set at the lower end (about 5 keV in lithium) by photoelectric absorption in the scattering material and at the upper end by the rapid decrease in flux from the X-ray sources. Since the efficiency of all polarimeters is quite low, it is essential to go to great lengths to reduce the non-X-ray background. In the case of Bragg crystal polarimeters, this may be accomplished in part by mounting the crystals on an arc of a parabolic surface so that the reflected X-rays are focused onto a small detector. This results in a substantial reduction in the size of the detector and yields a commensurate reduction in the non-X-ray background event rate. This type of polarimeter has been discussed in detail elsewhere (Weisskopf *et al.*, 1972). The Thomson-scattering polarimeter has been discussed by Angel *et al.* (1969), by Wolff *et al.* (1970), and by Tindo *et al.* (1970). The Thomson-scattering and graphite polarimeters have been flown in several rocket flights by the X-ray astronomy group at Columbia University. This work has culminated in the detection of X-ray polarization from the Crab Nebula as described below. The Thomson-scattering polarimeters constructed by the group at the Lebedev Institute in Moscow have been flown on Intercosmos 1 and 4. These have been used to study solar flares and, as indicated above, this group has detected strong solar flare X-ray polarization. This work has recently been summarized by Tindo *et al.* (1971). Bragg-crystal polarimeters are scheduled to be flown on the UK-5 and OSO-I satellites. The UK-5 instrument also serves as a spectrometer and therefore employs a flat crystal.

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The OSO-I instrument uses a parabolic array of mosaic graphite crystals. Two complete polarimeters will be installed on the spacecraft, and their axes will be roughly orthogonal so as to provide both of the Stokes linear polarization parameters simultaneously. The OSO-I instrument is mounted in the bottom of the wheel section of the OSO vehicle with the polarimeter axis parallel to the spin axis of the wheel.

Sources will be selected by pointing the spin axis toward the source; under normal flight conditions, it will be possible to observe a source for several days. The wheel rotation, of course, provides the desired rotation of the polarimeter to help eliminate spurious systematic effects. The predicted performance of the instrument in both first order, 2.6 keV, and second order, 5.2 keV, for several interesting sources is shown in Table I.

TABLE I

Percent minimum detectable polarization at 3-σ, 99 % confidence level

Source	Observing time (days)	2.6 keV only (%)	5.2 keV only (%)	Combined result (%)
Crab Nebula (Tau X-1)	1	1.8	3.8	1.7
Sco X-1	1	0.59	1.1	0.52
Cyg X-1	1	4.4	9.0	4.0
M 87 (Vir X-1)	1	7.6	18	7.3
Nor X-2	1	2.4	3.9	2.0
Sco X-2	1	2.7	3.8	2.2
Crab Primary Pulse	6	7.0	18	7.0
Cen X-3 (each of four 0.25-s bins within pulse)	6	17	6.4	6.1

It has been proposed to fly a focal plane Bragg crystal polarimeter on the HEAO-C spacecraft. The instrument will be located at the focus of the high-efficiency lens, and it can be used for polarization mapping of extended sources.

The nonsolar X-ray polarization observations that have been made so far have been restricted to Sco X-I and the Crab Nebula. It has been shown that polarization of Sco X-1 is less than 20% (Angel *et al.*, 1969). This result is entirely consistent with the view that Sco X-1 is a thermal X-ray source. The determination of whether or not Sco X-1 has a small polarization that might arise from scattering within an accretion disk must await the flights of UK-5 and OSO-I. As indicated above, two rocket experiments that have been performed on the Crab Nebula by Wolff *et al.* (1970) and Novick *et al.* (1972) have demonstrated that the X-ray emission from this object is polarized. The magnitude and position angle of the polarization are $(15.4 \pm 5.2)\%$ and $(156 \pm 10)^\circ$, respectively (Novick *et al.*, 1972). This is to be compared to the polarization in the optical of 14% 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. The equality of the observed X-ray and optical polarizations and the fact that the spectrum can be represented by a power law confirm the view that the synchrotron process is responsible for the X-ray emission. No X-ray polarization would have been observed if the thermal model of Sartori and Morrison (1967) obtained. Thus, the Crab Nebula is the

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first X-ray object for which we have confirmed emission mechanism. This observation poses new problems for pulsar theories since it implies that the synchrotron electron spectrum extends to 6×10^4 GeV if the Nebular magnetic field is taken as 10^{-4} G. Since the radiative lifetime for such electrons is a fraction of a year, they must either be continuously generated by the pulsar, or they must be continuously accelerated by magnetic dipole radiation from the pulsar (Gunn and Ostriker, 1971; Rees, 1971) or by some other presently unknown process. Continuous injection of 6×10^4 GeV electrons appears to be impossible since in the high magnetic field (10^{12} G) of the pulsar the electrons will lose their energy by either synchrotron or curvature radiation before they escape from the immediate neighborhood of the pulsar (Ruderman, 1972). Continuous acceleration by magnetic dipole radiation seems to be ruled out by the fact that Landstreet and Angel (1970) failed to find the circular polarization in the optical band that had been predicted by Rees (1971) for this process. Thus, it appears that we must look elsewhere for either an injection or acceleration mechanism.

From the above discussion, it is clear that both spectroscopy and polarimetry are destined to play an important role in X-ray astronomy. However, most of the critically important results must wait until the various satellite instruments are in orbit.

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