SPECTROSCOPY IN THE 10 keV TO 10 MeV RANGE

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ABSTRACT

Spectral lines in the 10 keV to 10 MeV range carry information of fundamental importance on many of the objects discussed at this workshop. Since the lines are directly related to specific physical processes this information is model independent and gives the physical conditions in the objects. At the sensitivities achieved to date, $\sim 10^{-4}$ to 10^{-3} ph/cm^2-sec for steady sources and $\sim 10^{-2}$ to 1 ph/cm^2-sec for transient sources, lines have been detected from the galactic center, gamma-ray bursts and transients, X-ray pulsators, the Crab pulsar and solar flares. Future instruments with a factor of $\sim$ 100 sensitivity improvement will allow detailed spectroscopic study of these classes of objects as well as supernova remnants, active galaxies and the interstellar medium. This sensitivity improvement can be obtained through the use of detector technology already proven in balloon and satellite instruments.

I. INTRODUCTION

Observations of spectral lines in the high energy range, 10 keV to 10 MeV, are directly related to the understanding of many of the classes of objects discusses at this workshop. Neutron stars, black holes, supernova remnants, the interstellar medium, the galactic nucleus and active galactic nuclei are known or predicted to be sources of spectral lines which can be studied with high-energy spectroscopy. Line forming processes with photon energies above 10 keV are a natural consequence of the $> 10^8$K temperatures and $> 10^{12}$ gauss fields which occur in or near these objects. The lines are due to electron-positron annihilation, cyclotron processes, radioactive decay, and nuclear deexcitation following inelastic collison or neutron capture. Since the lines are directly related to specific physical processes, they carry model-independent information on the physical conditions in the objects: temperature, density, bulk motion, abundance of isotopic species, the state of matter, the energy spectrum of particles and the mass of a central object. This information can be used to guide theoretical modeling and provide critical tests of models in order that the nature of the objects may be determined.

The major difficulty in the development of the field of high energy spectroscopy has been the attainment of sufficient sensitivity. The early predictions by Morrison (1958) indicated line fluxes greater than 10^{-2} ph/cm^2-sec from steady sources. However, the strongest steady sources have now been observed to have fluxes of $\sim 10^{-3}$ ph/cm^2-sec and so their detection has only been possible with the improved instruments available in the last few years. Lines have now been detected in at least 41 different objects representing 6 classes of astrophysical phenomena. These include 9 impulsive solar flares (Chupp 1981) and 27 gamma-ray bursts (Mazets et al. 1981) where line features are characteristic rather than exceptional.

In this paper I review the line forming processes, the physical information carried by the lines and their energy distribution and expected widths. Then the observed and predicted fluxes are used to derive the instrumental sensitivities required for effective future observations. Finally, instrument concepts which can achieve these sensitivities are presented.

II. PHYSICAL PROCESSES OF 10 keV TO 10 MeV LINE FORMATION

In systems with effective temperatures greater than $\sim 10^8$K and/or magnetic fields greater than $\sim 10^{12}$ gauss line emission above 10 keV will occur by several processes. These have been reviewed by Ramaty (1978), Ramaty and Lingenfelter (1979) and Ramaty et al. (1981).

a) Cyclotron Processes

Cyclotron lines result from transitions between the Landau levels of electrons in strong magnetic fields. The $\sim$50 keV line in the binary X-ray pulsator Her X-1 is interpreted as due to either cyclotron absorption or emission and indicates a field of $\sim 5 \times 10^{12}$ gauss (Trümper et al. 1978). The shift of the line energy with phase of the 1.24 sec pulsation (Gruber et al. 1980) is apparently due to beamed emission from different field regions being responsible for the pulsed emission. Cyclotron absorption has been observed at $\sim$ 20 keV in the transient binary X-ray pulsator 4U0115+63, requiring a field of $\sim 2 \times 10^{12}$ gauss (Wheaton et al. 1980). The $\sim$ 50 keV absorption features observed in gamma-ray bursts have been interpreted as due to cyclotron processes indicating that highly magnetized neutron stars are the site of the bursts (Mazets et al. 1981). Since the cyclotron line width is a sensitive function of the magnetic field geometry (Bussard 1980), future high sensitivity spectroscopic observations will determine the magnetic field structure in the emission regions of all these objects and its temporal evolution in the case of gamma-ray bursts. A sensitive search for cylotron lines in X-ray bursters and galactic bulge sources could establish whether these objects contain highly magnetized neutron stars and determine their relationship to X-ray pulsators and gamma-ray bursts (Lamb 1981).

b) Electron-Positron Annihilation

Positrons are produced by pair production, inelastic collisions and radioactive decay of nucleosynthesis products. Since the 511.003 keV annihilation quanta have an exactly known energy in the rest frame, spectroscopic observations can provide a great deal of information. Line broadening would indicate the temperature and/or Keplerian or radial motion of the annihilation site. When positron lifetime information exists the line width could be used to determine the density of the positron slowing down region as well as limit the mass of a central object. A line centroid shift would indicate a gravitational redshift or a Doppler red- or blueshift. Figure 1 shows the galactic center 511 keV line measured by HEAO-3 (Riegler et al. 1981). The 2.5 keV limit on the line width and observation of variability in 6 months require $T < 7 \times 10^4$ K and a central mass $< 2 \times 10^7 M_\odot$. A remarkable feature of the galactic center annihilation radiation is that its luminosity, $\sim 5 \times 10^{37}$ erg/sec, is a factor of $\sim$ 200 greater than that of the brightest 1-4 keV source in the GCX complex (Watson et al. 1981). Further theoretical and observational study of the annihilation radiation will be crucial to the understanding of the galactic nucleus.

The redshifted annihilation lines seen in the spectra of gamma-ray bursts at $\sim$ 400 keV can obtain up to 10 percent of the burst energy and can vary on shorter time scales than the total luminosity (Mazets et al. 1981) Ramaty et al. (1980) have interpreted the $\sim$ 400 keV line in the 5 March 1979 burst as due to annihilation of positrons produced by pair production in the radiation dominated, high temperature atmosphere of a neutron star which is heated to $T \sim 10^9$K and magnetically confined. Confinement is necessary to produce gravitationally redshifted rather than Doppler blueshifted annihilation radiation.

Pair production should occur when a radiation field's characteristic temperature exceeds $\sim 10^9$K. Since this is observed to occur in accretion fueled emission near black holes such as Cyg X-1 and those thought to exist at the centers of active galaxies, these objects should be sources of 511 keV photons (Lightman 1981). Observations of this radiation would significantly aid models of these objects and improve the understanding of their relationship to the galactic nucleus.

c) Radioactive Decay

Gamma-ray lines are predicted to be produced by the radioactive decay of the products of explosive nucleosynthesis events in supernovae and novae (Clayton 1980, Woosley and Axelrod 1980). Although none of these lines has been discovered, the predicted fluxes are within the sensitivity of future instruments based on today's techniques. Since the gamma-rays' flux directly indicates the abundance of the relevant isotope, the abundance of synthesized material may be measured in a model independent manner. In contrast, the interpretation of atomic lines in the few keV range to determine abundances in an expanding supernova remnant is a model dependent procedure made particulary difficult since thermodynamic equilibrium does not occur. Earlier at this workshop Shull (1981) described these difficulties and the resulting large uncertainties in elemented abundances.

Gamma-ray lines can provide additonal important information. Used as tracers they can identify the positions of the galactic supernovae which have occurred in the past $\sim$ 300 years This does not appear to be possible in any other wavelength band. The Doppler broadening of the lines give the expansion velocity of the core of the supernova remnant, not the velocity of the shock-heated outer envelope which is measured optically. Ratios of gamma-ray lines give the density of the envelope which overlays the synthesized material (Clayton 1974). Long lived isotopes indicate the total rate and sites of galactic nucleosynthesis over the last $\sim 10^6$ years. These observations would provide detailed tests of the highly developed models of supernova and nova explosions and make the study of young galactic supernova available to other wavelength ranges.

d) Nuclear Deexcitation

Gamma-ray line production by nuclear deexcitation is expected whenever the particle energies exceed the threshold for nuclear reactions, typically a few MeV. The expected nuclear gamma-ray emissivities for temperatures in the 10^8-10^{12}K range have been calculated by Higdon and Lingenfelter (1977), Ramaty et al. (1979) and Ramaty et al. (1981). Since several hundred MeV/nucleon must be released in accretion onto a neutron star, it is expected that nuclear reactions should be a significant process near these objects. Neutrons would be produced by many of the reactions and interact themselves by inelastic scattering and neutron capture. The result of all these reactions would be excited nuclei which would produce characteristic nuclear gamma-rays. These indicate the composition of the medium as well as the energy spectrum of the fast particles. Line widths indicate the state of matter since large Doppler broadening occurs in lines from an ambient gas while small broadening occurs in dust and solids. Particle beaming results in a Doppler shift of the line energy due to the recoil of the excited nuclei. A gravitational redshift indicates the M/R value of the central object. Since the neutron thermalization time is density dependent, the time delay of neutron capture gamma-rays indicates the ambient density.

Nuclear gamma-rays have been observed in the 19 November 1978 gamma-ray burst at $\sim$ 740 keV, presumably due to gravitationally redshifted 847 keV gamma-rays from the first excited state of ^{56}Fe (Teegarden and Cline 1980). The 20-minute transient observed on 10 June 1974 from a balloon had a spectrum that consisted of four intense lines (Jacobson et al. 1978). Lingenfelter *et al*. (1978) have interpreted this event as due to episodic accretion onto a neutron star resulting in gravitationally redshifted ($z \simeq .20$ to $.29$) lines due to electron-positron annihilation (511→413 keV) and neutron capture by hydrogen (2223→1790 keV) and iron (7639→5946 keV) as well as a non-redshifted line due to neutron capture by hydrogen (2223 keV).

Nuclear gamma-rays, as well as the electron-positron annihilation line, have also been observed in solar flares where protons are accelerated to several hundred MeV/nucleon and produce excited nuclei in the solar atmosphere by inelastic excitation and neutron capture (Chupp *et al* 1973, Hudson *et al*. 1980). Recently the SMM Gamma-Ray Spectrometer has detected lines from 6 flares and the interpretation of these results indicate that electrons and ions are accelerated simultaneously during the impulsive phase of the flare and that this occurs even in relatively small impulsive flares (Chupp 1981).

Nuclear gamma-rays are predicted to be produced in the interstellar medium due to the interactions of cosmic-rays and the ambient medium. Ramaty *et al*. (1979) have calculated the line intensities and widths under various assumptions of composition and cosmic-ray energy. The ratios of the fluxes of various gamma-ray lines is a sensitive function of cosmic-ray energy at energies less than $\sim$ 100 MeV/nucleon. In addition, the lines indicate the spatial distribution and composition of the interstellar dust and gas. Figure 2 shows the predicted gamma-ray spectrum from the direction of the galactic center. The intensities and widths of these lines carry detailed information on 13 nuclides and the low-energy cosmic-ray spectrum.

III. LINE ENERGIES AND WIDTHS

The energy distribution of the lines due to the processes described above are shown in Figure 3. Cyclotron lines occur in the 10 keV to 100 keV range, but could occur at higher energies if the magnetic field exceeds 10^{13} gauss. Electron-positron annihilation lines occur in the $\sim$ 400 to 511 keV range and radioactive decay lines extend from $\sim$ 10 keV up to a few MeV. Nuclear lines due to inelastic excitation occur in the 300 keV to $\sim$ 10 MeV range and neutron capture lines occur from $\sim$ 2 MeV to $\sim$ 10 MeV. Also indicated in Figure 3 are the processes and line energies that have been observed or predicted in various objects. These lines span the entire 10 keV to 10 MeV range and it is clear that spectroscopic observations over the entire range are required to study these objects.

The widths of the various lines are shown in Figure 4. The distinction between resolved and non-resolved lines is important. When the line is resolved, i.e. its profile is measured, much additional information is obtained. The indicated width of non-resolved lines is an upper limit which results from low statistical significance and/or the inability to time-resolve a variable source. Also shown in Figure 4 are the energy resolution of NaI and Ge. These indicate that NaI is incapable of determining the width of most of the lines while Ge could do this for nearly all of them. Thus Ge detectors are required for spectroscopic observations in the 10 keV to 10 MeV range. Small HgI$_2$ detectors are now available and in the future they may also be suitable (Richer 1981).

IV. REQUIRED INSTRUMENT SENSITIVITY FOR FUTURE OBSERVATIONS

The required line sensitivity for effective spectroscopic studies can be determined from a consideration of the line fluxes of the objects detected to date. These are indicated in Figure 5. Because of the short duration of the gamma-ray bursts only very intense fluxes, $\sim$ 1 ph/cm^2-sec, have been observed from them. Somewhat weaker fluxes, $\sim$ .01-1 ph/cm^2-sec, have been observed from solar flares and the 20-minute transient detected from a balloon. The galactic center, X-ray pulsators, and the Crab pulsar produce quasi-steady lines in the 1 to 4 x 10^{-3} ph/cm^2-sec range. All these fluxes have been near the instrumental sensitivity limits so detections have typically been in the 3 to 10σ range. Although these have indicated the existence and flux of the lines, they have usually not given details on the lines' temporal behavior, width and exact energy.

Also shown in Figure 5 are the instrument sensitivities achieved to date and those required for future instruments. The HEAO-3 instrument (Mahoney et al. 1980) used 4 large coaxial Ge detectors in an instrument optimized at ∿ 1 MeV. Below ∿ 60 keV the instrument was cut off due to detector dead layers. The sensitivity varied from ∿ 10^{-4} to 10^{-3} ph/cm^2-sec, depending on energy. Since HEAO-3 was a scanning spacecraft, ∿ 30 days were required to observe a source during which ∿ 100 hours of effective time on a point source occurred. The sensitivity that present balloon instruments which are optimized at ∿ 1 MeV can obtain in a single balloon flight (not shown in Figure 5) is a factor of ∿ 2 worse than that of HEAO-3. The sensitivity of present balloon instruments which are optimized at ∿ 60 keV, also shown in Figure 5, is 2 x 10^{-4} ph/cm^2-sec at 60 keV. Balloon instruments planned for the next 5 years will have a factor of ∿ 4 improvement over this sensitivity.

Gamma-ray lines have been observed from all the objects indicated in Figure 5 which have a flux > 10^{-3} ph/cm^2-sec. However, the number of observations have been restricted to only the brightest objects in each class and therefore the scientific results have been limited. The predicted fluxes from galactic supernovae are ∿ 10^{-4} ph/cm^2-sec, just below present sensitivities. However, the predicted fluxes from extragalactic supernovae and the interstellar medium are a factor >10 lower, in the 3 x 10^{-6} to 7 x 10^{-5} ph/cm^2-sec range.

From these considerations of source fluxes one concludes that the potential of high energy spectroscopy will be realized when two basic conditions are fulfilled:

1. A sensitivity of 10^{-6} to 10^{-5} ph/cm^2-sec is achieved for (quasi-) steady sources and ∿ 10^{-4} to 10^{-2} ph/cm^2-sec for transient sources. This will allow the measurement of the predicted lines from galactic and extragalactic supernovae as well as the interstellar medium. It will also assure that detailed studies of lines will be performed on objects ∿ 10 times fainter than have been detected to date and that line features will be detected in objects that are ∿ 100 times fainter than those detected to date.

2. Observations are conducted from space and in missions with years of duration. This will assure that a large number of objects are studied in order to learn their class properties as well as discover line emission from unsuspected sources.

The following examples indicated illustrate these requirements. The gamma-ray burst in which Teegarden and Cline (1980) detected redshifted line emission from ^{56}Fe at 3.5σ significance had a total energy flux of $\sim 3 \times 10^{-4}$ erg/sec. Since bursts of this intensity occur only ~ once/year (Jennings and White 1980) both greater sensitivity and years of observation are required to obtain high quality spectroscopic data on a large number of gamma-ray bursts. At 100 times better sensitivity $> 20\sigma$ detections of the 847 keV Fe line would be expected in 10 to 20 bursts per year and detailed analysis could be performed on the class of gamma-ray burst sources. Similar considerations apply to steady sources. For example, the pulse-phase resolved study of the Her X-1 cyclotron line requires ~ 10 times the present sensitivity and the opportunity to observe the entire 35-day cycle of Her X-1. A similar study of the ~ 100 galactic objects brighter than a few UFU requires an additional factor of ~ 10 sensitivity improvement.

V. CONCEPTS FOR FUTURE SPECTROSCOPY INSTRUMENTS

The sensitivity requirements developed above can be fulfilled by a combination of three instruments which are based on technology used in today's balloon and satellite instruments. Each instrument is optimized for a specific energy range and field of view. All the detectors would be germanium since it is capable of resolving nearly all the expected lines and is available today in large volume geometries, ~ 150 cm^3. The objects for which the instruments are suited, their physical parameters and sensitivities are given in Table I. The sensitivities of the instruments are also indicated in Figure 5.

Instrument (1) is for the study of (quasi-) steady sources of lines in the 10 keV to ~ 600 keV range. Optimum sensitivity would occur at ~ 60 keV. A field of view of a few degrees would be provided by a passive collimator in order to reduce background and source confusion. Planar detectors would provide 40 times the collecting area of present instruments, an energy resolution of $\lesssim 1$ keV and minimum background.

Instrument (2) is for the study of transient sources. It would cover the 10 keV to 10 MeV energy band and observe the entire sky. Since detector volume determines sensitivity above a few hundred keV, the volume would be ~ 60 times that of the Teegarden and Cline (1980) detector. Unshielded co-axial detectors would be used in order to have good sensitivity above a few hundred keV.

Instrument (3) is for the study of (quasi-) steady sources of lines in the 100 keV to 10 MeV range. Optimum sensitivity would occur at a few MeV. The detector volume is 25 times that of HEAO-3 and very long observing times, ∿ 200 days, would be required to reach the desired sensitivity. Because of this, a wide field of view, ∿ 40°, with a coded aperture would be required to observe an acceptable number of objects during a several year mission. Heavily shielded coaxial detectors would be used in order to have minimum background and good sensitivity at the highest energies.

All the instruments would require cooling of the detectors to ∿ 90K. On HEAO-3 this was done with a solid cryogen refrigerator with lifetime of only ∿ 6 months. Mechanical refrigerators have also been used for germanium detector cooling in space (Nakano and Imhoff 1978), but have had problems with reduced efficiency in extended life also caused microphonic noise in the detector signal. The problems with mechanical refrigerators can be solved with a modest development program and in the 1990's they will be the preferred method of achieving the required detector temperatures.

Radiation damage was a problem with the p-type HEAO-3 detectors (Mahoney et al. 1981). However, the n-type detectors which are now commercially available are unaffected by radiation damage in a low earth orbit. These detectors also have a negligible dead layer, so they operate from < 10 keV to > 10 MeV.

VI. CONCLUSION

Future observations of spectral lines in the 10 keV to 10 MeV range will be of fundamental importance in our understanding of a wide variety of objects and phenomena which have been discussed at this workshop. These include neutron stars and black holes and processes near them, explosive nucleosynthesis and supernova remnants, solar flares, the interstellar medium, the galactic center and active galactic nuclei. Spectral lines have already been detected from many of these by the modest instruments that have been used to date. These have achieved a sensitivity of 10^{-4} to 10^{-3} ph/cm^2-sec for steady sources and 10^{-2} to 1 ph/cm^2-sec for transient sources. The instrument concepts presented here would achieve a factor of 100 sensitivity improvement, allowing detail study of many objects. Since the lines are directly related to specific physical processes, model independent information on the physical conditions in the objects results and the class properties and nature of the objects can be determined.

The instrument concepts are based on detector technology that has already been developed for balloon and satellite instruments. Instruments using these concepts would easily be accommodated by a Shuttle-launched Explorer mission in the 1990's. Since the scientific return from such a mission would be both large and relevant to a wide variety of problems in high energy astrophysics it should be given the highest priority in the planning of future space missions.

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TABLE I

HIGH-ENERGY SPECTROSCOPY INSTRUMENTS FOR THE 1990's

Object/Phenomenon	Detector	Sensitivity
1. X-Ray Pulsator Pulsar Supernova Galactic Center Active Galactic Nucleus Black Hole	2000 cm^2 x 1.5 cm thick Planar Ge array Few ° FOV Up to 30 day observation 10 to 600 keV	$\sim 3x10^{-6}$ ph/cm^2-sec @ 60 keV. $\sim 3x10^{-5}$ ph/cm -sec @ 511 keV. Spectra of > 1 UFU source. Phase resolved spectra for > 10 UFU sources. Discover young galactic supernova via γ-ray lines < 600 keV. Discover 511 keV emission from active galactic nuclei.
2. Gamma-Ray burst (5 sec) Gamma-Ray Transient (20 min) Solar Flare (20 min)	2000 cm^3 Ge coax array > 2π FOV 10 keV to 10 MeV	Just detect Fe line in $3x10^{-6}$ erg/cm^2 burst (~150/yr). Detect Fe line @ >20σ in >$2x10^{-5}$ erg/cm^2 burst (~20/yr). $\sim 10^{-3}$ ph/cm^2-sec @ 1 MeV for a 20 min event. Detect the 20 min transient's lines @ ~60σ and strong solar flare's lines @ ~300σ.
3. Supernova Interstellar Medium Search for Unsuspected Sources of Gamma-Ray Lines	10,000 cm^3 Ge coax array ~40° FOV ~1° position determination Sensitive to point and diffuse sources 200-day observation 100 keV to 10 MeV	$\sim 5x10^{-6}$ ph/cm^2-sec @ 1 MeV. Measure > 100 keV gamma-ray lines from galactic and extragalactic supernovae. Measure and map the interstellar gamma-ray lines. Discover unsuspected sources of gamma-ray lines.

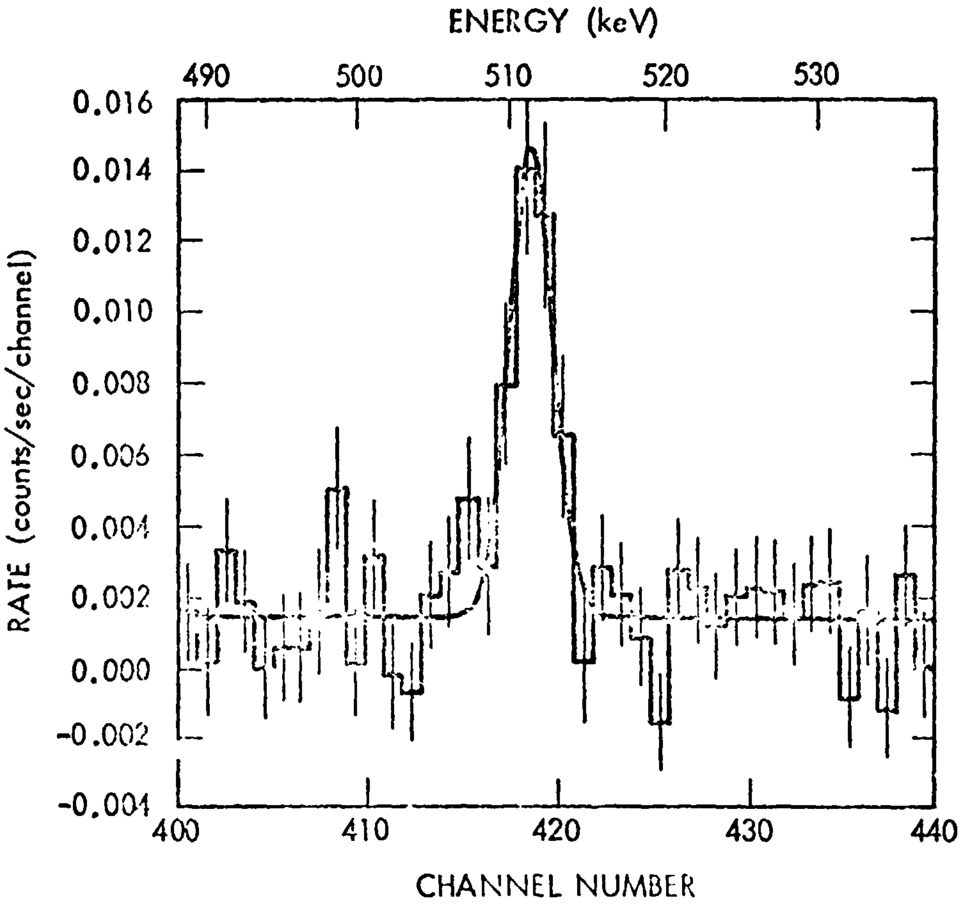

Figure 1. The spectrum of the galactic center region measured by HEAO-3 in Sept/Oct 1979 (Riegler *et al.* 1981). The 511 keV electron-positron annihilation line flux, (1.8 ± .2) x 10^{-3} ph/cm^2-sec, was found to be a factor of 3 lower when HEAO-3 reobserved the galactic center 6 months later. The observed line width is due to the 2.7 keV FWHM energy resolution of the detectors. These data constrain the galactic center line width to less than 2.5 keV (1σ) and 3.4 keV (2σ).

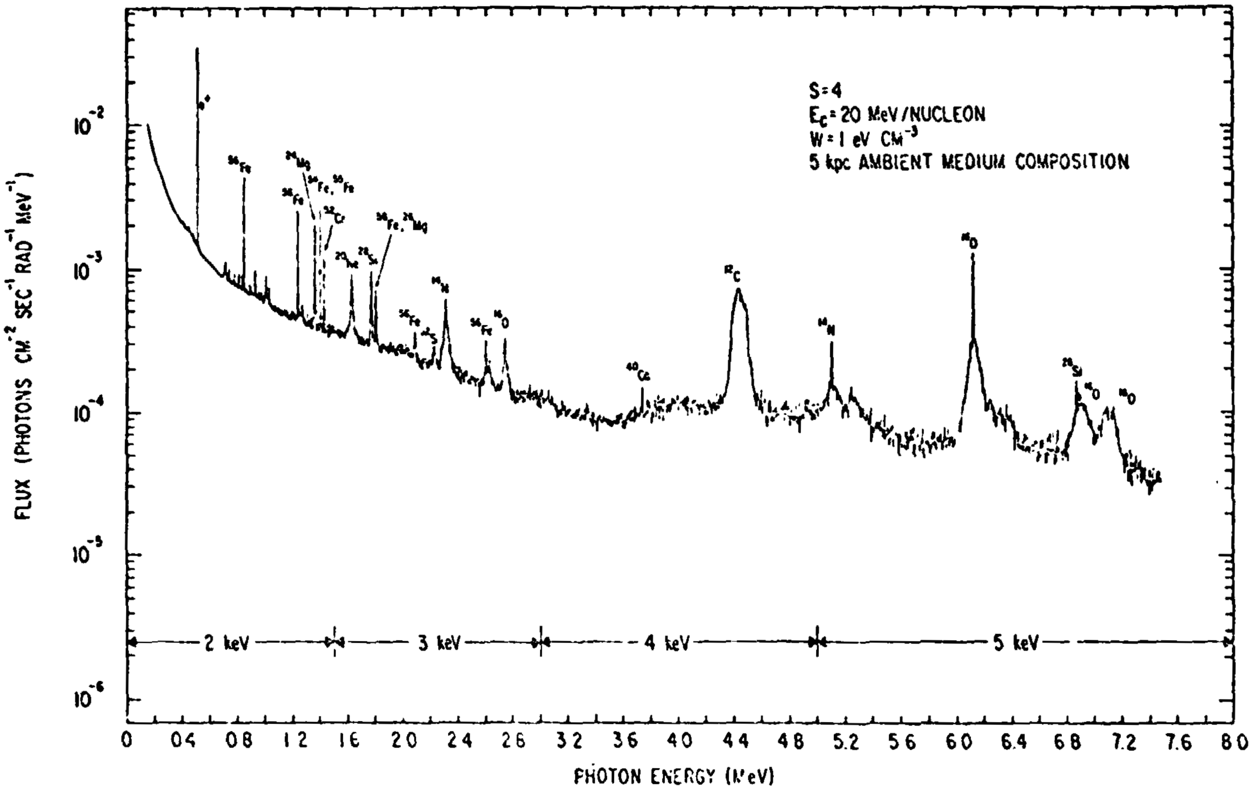

Figure 2. The predicted spectrum of gamma-ray lines and bremsstrahlung from the direction of the galactic center (Ramaty et al. 1979, Figure 30). Narrow lines are due to the excitation of nuclei in grains and wide lines are due to the excitation of nuclei in gas. The short lifetime of the 4.438 MeV level of ^{12}C, 5 x 10^{-14} sec, results in a broad line at this energy in both cases. The fluxes are typically ~10^{-5} ph/cm^{2}-sec-rad, a factor of ~20 below the best sensitivity achieved to date, but within the capabilities of the future instruments discussed in this paper.

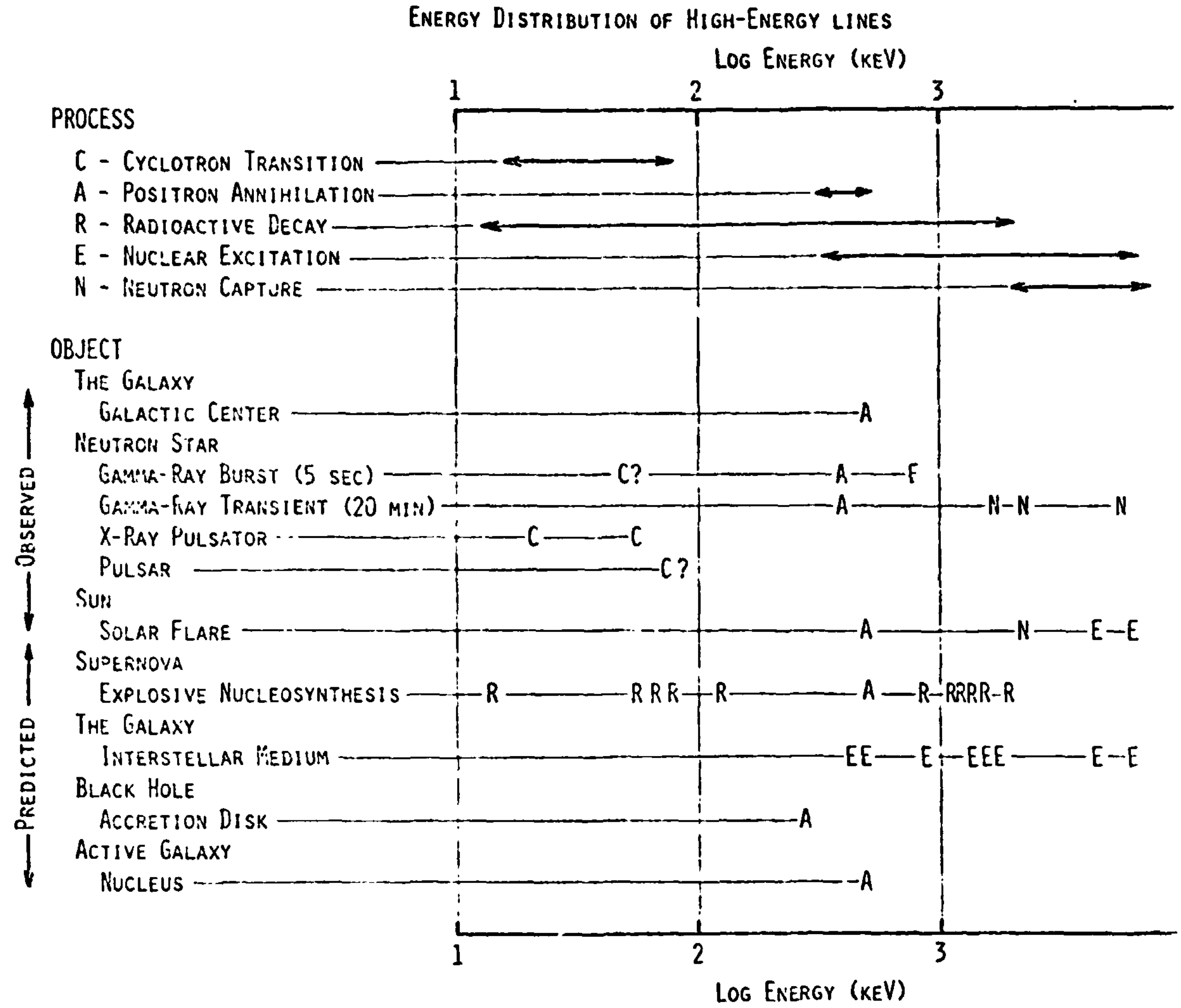

Figure 3. The energy distribution of lines produced by the processes discussed in the text. Also shown are the processes and energies of lines observed and predicted in a variety of astronomical objects.

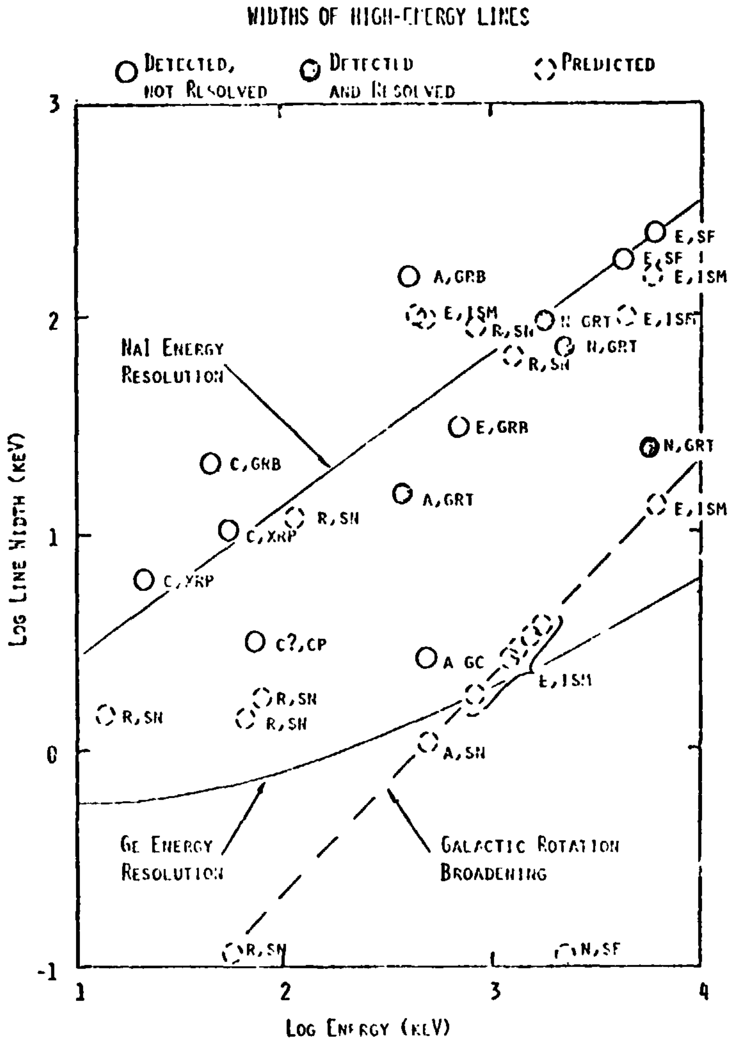

Figure 4. The widths of lines produced by the processes discussed in the text. The plotted width of a detected, but not resolved line is an upper limit to the line's true width. The energy resolution of Ge and NaI detectors are also plotted. It is obvious that Ge is required for detailed studies which measure the widths and profiles of lines. The processes and sources of the lines are indicated by the notation X,Y, where X = process and Y = source, as given below.

Process	
C	Cyclotron
A	Electron-positron annihilation
R	Radioactive decay
E	Inelastic excitation of nuclei
N	Neutron capture

Source	
GC	Galactic center
GRB	Gamma-ray burst
GRT	20-min gamma-ray transient observed from a balloon
SF	Solar flare
ISM	Interstellar medium
SNR	Supernova remnant, i.e. explosive nucleosynthesis
XRP	X-ray pulsator
CP	Crab pulsar

INTENSITIES OF HIGH-ENERGY LINES

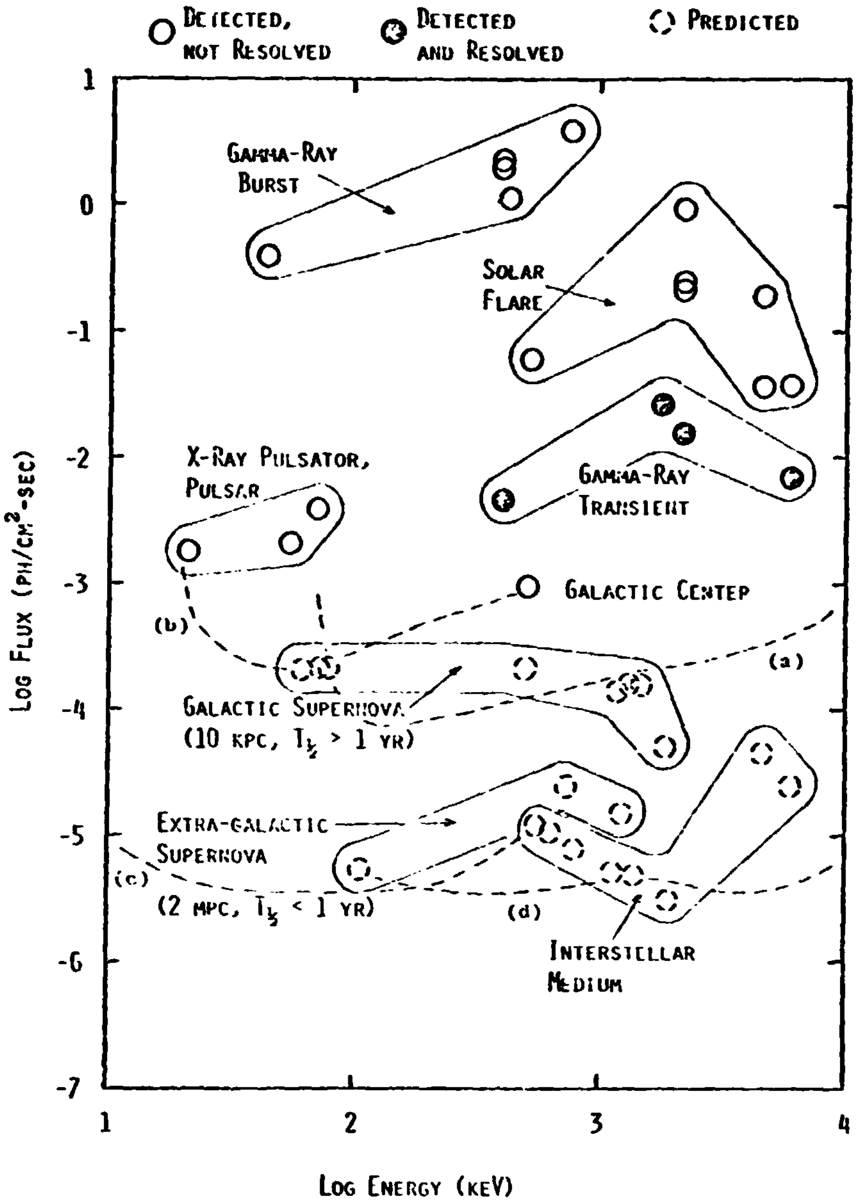

Figure 5. The intensities of high-energy lines. The most intense lines of each class of object are plotted. Also plotted are the sensitivities of several instruments.

(a) HEAO-3: 400 cm^3 coaxial Ge detector array, 30-days of scanning observation.
(b) Present balloon instrument: 50 cm^2 Ge detector array, 6 hour pointed observation.
(c) Future space instrument: Instrument (1) from the text, 2000 cm^2 planar Ge array, 30-day pointed observation.
(d) Future space instrument: Instrument (3) from the text, 10,000 cm^3 coaxial Ge array, 200-day observation.

C-7