N87-24259

12

NUCLEOSYNTHESIS AND ASTROPHYSICAL GAMMA RAY SPECTROSCOPY

Allan S. Jacobson
Earth and Space Science Division
Jet Propulsion Laboratory
4800 Oak Grove Drive
Pasadena, California 91109

1. INTRODUCTION

From its inception, one of the primary motivations for the development of astrophysical gamma ray spectroscopy has been the search for extra-solar system radioactivity. This interest stems from a desire to understand the processes which produced the large array of complex elements that make up our universe and that must have been synthesized subsequent to its creation in the Big Bang. Many of the isotopes produced in such processes are radioactive and their emissions are the key to the detection of their production sites and the identification of the processes involved. How closely the radionuclides and their sources are spatially correlated will, of course, depend upon their decay lifetime and the rate at which they diffuse into the interstellar medium. This topic of investigation was first suggested by Morrison [1958] in his pioneering paper outlining the potential of gamma ray astronomy.

Morrison pointed out that radioactive debris of nucleosynthesis in a supernova might be found in the Crab nebula, the remnant of a supernova explosion seen from Earth in 1054 A.D. Based upon the hypothesis that the decay of ^{254}Cf fueled the exponentially decaying light curve of the supernova [Burbidge et al., 1956] which gave birth to the nebula, he estimated that gamma rays from the decay of ^{226}Ra synthesized in the explosion would be observable today. Savedoff [1959] expanded on these predictions, listing several other radioisotopes which might be detectable if this hypothesis were true. He estimated that the strongest lines would be at 60 keV from ^{241}Am, and at 180 keV from ^{251}Cf with current fluxes of about 10^{-2} photons/cm^2-s.

Clayton, in a large body of theoretical work [for an example of one such reference, see Clayton, 1982], has firmly established the idea that astrophysical gamma ray spectroscopy is a valuable tool with which to test the theoretical models of nucleosynthesis and to probe the structure of the sites of these high energy processes. He pointed out [Clayton, 1984] that the detection of radioactivity would provide a new cornerstone for theoretical investigations. It was primarily the detailed calculations by Clayton and Craddock [1965] of the gamma rays expected from the Crab nebula under the ^{254}Cf hypothesis which stimulated the earliest flight of a germanium-based high resolution gamma ray spectrometer to search for extra-solar system radioactivity [Jacobson, 1968].

Subsequent theoretical work has shown that the synthesis of ^{254}Cf falls several orders of magnitude short of that required to power the supernova light curve. However, deeper understanding of the processes involved has yielded several other synthesized radioisotopes whose gamma ray line emissions are currently likely candidates for observation. Isotopes produced in Type I supernova are listed in Table 1 [from Lingenfelter and Ramaty, 1978]. The most abundant of these is ^{56}Ni [Clayton, Colgate, and Fishman, 1969]. This isotope decays with a mean life of 8.8 days to ^{56}Co, which has a mean life of 114 days. It decays in turn to ^{56}Fe. Twenty percent of the ^{56}Co decays via positron emission. While the output of gamma ray lines is expected to be intense, a combination of the relatively short lifetimes, dense and absorptive ejecta, and high-expansion velocities with concomitant large Doppler broadening make these lines difficult to observe. Longer lived radionuclides such as ^{26}Al, ^{60}Fe [Clayton, 1974, 1975] and ^{22}Na expected to be produced in abundance with novae [Clayton and Hoyle, 1974] present somewhat greater prospects for observation. Ramaty and Lingenfelter [1977] first noted for reasons discussed below that ^{26}Al would likely be the most detectable of all the radioactive products.

Guided by the list of expected lines in Table 1, a systematic search for cosmic radioactivity was undertaken using the Jet Propulsion Laboratory (JPL) high

Table 1. Gamma ray producing decay chains from explosive nucleosynthesis for an ejecta mass of 1 M_O [from Lingenfelter and Ramaty, 1978].

DECAY CHAIN	MEAN LIFE (yr)	NUCLEI/ SUPERNOVA	PHOTON ENERGY (MeV)	PHOTONS/ DISINTEGRATION
$Ni^{56} \rightarrow Co^{56} \rightarrow Fe^{56}$	0.31	3×10^{54}	0.847	1
			1.238	0.70
			2.598	0.17
			1.771	0.16
			1.038	0.13
$Co^{57} \rightarrow Fe^{57}$	1.1	7×10^{52}	0.122	0.88
			0.014	0.88
			0.136	0.12
$Na^{22} \rightarrow Ne^{22}$	3.8	3×10^{52}	1.275	1
$Ti^{44} \rightarrow Sc^{44} \rightarrow Ca^{44}$	68	6×10^{51}	1.156	1
			0.078	1
			0.068	1
$Fe^{60} \rightarrow Co^{60} \rightarrow Ni^{60}$	2.2×10^6	5×10^{50}	1.332	1
			1.173	1
			0.059	1
$Al^{26} \rightarrow Mg^{26}$	1.1×10^6	4×10^{50}	1.809	1

resolution gamma ray spectrometer which flew aboard the HEAO-3 spacecraft. This search resulted in the discovery of ^{26}Al in the interstellar medium [Mahoney et al., 1982; Mahoney et al., 1984].

2. THE HEAO-3 MISSION

The HEAO-3 high resolution gamma ray spectrometer [Mahoney et al., 1980] was the first such instrument to perform an all-sky survey for gamma ray line emissions. It consisted of four approximately 100 cm^3 high purity germanium crystals actively shielded by 6.6 cm thick cesium iodide crystals in a well-crystal configuration. The aperture was defined by another cesium iodide crystal with a hole drilled through it above each of the Ge crystals, angular collimation of about 30° full width at half maximum (FWHM). A thin plastic scintillator over the aperture provided discrimination against charged particles. Cooling for the Ge crystals for their lifespan of 8.5 months was provided by a two-stage sublimation cooler containing solid methane and ammonia. The instrument made measurements over an energy range of 50 keV to 10 MeV, with an effective area of 72 cm^2 at 100 keV, 27 cm^2 at 500 keV, and 20 cm^2 at 1.5 MeV. A 3-sigma detection sensitivity threshold for a point source was about 2×10^{-4} photons/cm^2-s. The spectral resolution upon initial operation in orbit was 3 keV FWHM at 1.5 MeV.

The HEAO-3 spacecraft was launched on September 20, 1979 and operated until the mission ended on May 30, 1981. The germanium detectors functioned until cryogen exhaustion on June 1, 1980. Subsequent measurement of gamma ray phenomena such as solar flares and gamma ray bursts with the relatively low resolution cesium iodide detectors continued throughout the remainder of the mission. Scanning with a period of 20 minutes, with the spin axis aligned along the sun-earth direction provided a full celestial survey in a six-month period. Additionally, at the beginning of each six-month period, when the solar cell orientation with respect to the Sun made it possible, the spacecraft spin axis was aligned approximately along the galactic spin axis for two weeks, allowing the instrument to scan directly in the galactic equatorial plane.

3. THE HEAO-3 ANALYSIS AND RESULTS

The strategy of looking for radioactive nucleosynthesis materials by concentrating on diffuse galactic emission was suggested by Ramaty and Lingenfelter [1977], in their consideration of supernova ejecta, and by Clayton and Hoyle [1974] in their discussion of nova ejecta. Specifically, they pointed out that isotopes with high production yields and long lifetimes compared with the mean time between the synthesizing events would present the best candidates for detection since they would be observed as diffuse sources which are the cumulative product from a large number of events. In addition, the long lifetime enables the ejecta to slow from its initial velocity to that of the ambient medium before its decay so that the emitted line is not significantly Dopplerbroadened, further enhancing its detectability. Such lines would exhibit broadening only from galactic rotation, which is no more than about 3 keV.

In carrying out such a search, the systematic problems due to background radiation effects are formidable. The radiation background experienced by a spacecraft-borne gamma ray spectrometer in each orbit is complex in both its constituency and its temporal behavior. Cosmic rays modulated by the Earth's magnetic field constantly bombard the spacecraft and its payload, producing a large variety of secondary radiations including gamma ray lines coincident in energy with many of astrophysical importance. Additional radioactivation of the instrument and spacecraft materials and subsequent gamma ray line emission also result from the spacecraft's passage through trapped radiation in the South Atlantic Anomaly (SAA), which occurs several times a day. The primary component of the continuum background results mainly from the modulated cosmic rays and their secondaries and hence is also a function of the magnetic latitude. Auroral X-ray events and clouds of precipitating electrons also contribute their share to the background. These radiation components have characteristic temporal behavior spanning the full range from almost periodic with frequencies on the order of an hour, to transient and exponentially decaying with time constants as small as the order of milliseconds. The analysis is further complicated by a beating between the spacecraft spin period and the orbital period. Accumulating data over many days from a position in the celestial sphere which contains a source of interest, and then comparing that with an equivalent accumulation from a position presumably containing no sources, even when taking as much care as possible that all other parameters such as magnetic latitude, and time since SAA transit, are equal, yields unreliable results. Experience with such difficulties has led to the development of another approach to analyzing data obtained using scanning techniques [Wheaton et al., 1987]. In this approach, each 20-minute scan of the HEAO spacecraft is analyzed independently. Corrections for aperture response are made, and background obtained during the same scan is subtracted. The net result of many scans is then accumulated to give the final net flux.

Since the instrument sensitivity does not allow a measurement of the spatial distribution of a low intensity diffuse source, a model must first be hypothesized and then compared to the data. In analyzing the galactic plane data in the effort to discover an ^{26}Al component, each scan was fitted with an assumed distribution. While several models have subsequently been used, as discussed below, the initial distribution assumed was that of 100 MeV galactic gamma rays, which is consistent with an extreme population I. The fit included the folding in of instrumental parameters such as detector efficiencies, shield transmission, and the modulation of the source by the Earth. The presence of the Earth was crucial in this approach because it chopped the source emission allowing the background flux level to be established. Because neutron interactions on the ^{27}Al of the spacecraft and instrument produce excited ^{26}Mg, there is a fairly strong instrumental background flux at 1809 keV, the energy of the expected ^{26}Al radiation. The spectral vicinity of the line of interest is shown in Figure 1. It was helpful to the analysis that in close proximity to the target line there was another line at 1778 keV, also produced by neutron interactions on ^{27}Al, and a line at 1764 keV due to the presence of natural ^{238}U contaminants in the instrument materials. A test of the validity of any method used to bring out an astrophysical component of the 1809 keV line is that it must also eliminate these other close lines known to be of background origin.

Figure 2 shows the net result of the analysis. The control emission lines have indeed been removed by the process, leaving a net 1808 keV flux of cosmic origin.

The analysis yields a net line flux of $(4.8 \pm 1.0) \times 10^{-4}$ photons/cm^2-s-rad from the direction of the galactic center. The line has a width of less than 3 keV FWHM, and peaks at an energy of 1808.49 ± 0.41 keV. The accepted energy of the gamma ray line due to the decay of ^{26}Al is 1808.65 ± 0.07 keV.

An effort has been made to better understand the spatial distribution of the gamma ray emission. This is vital to any determination of its source. Distributions other than that of the high energy gamma rays have been fit to the data [Mahoney et al., 1985]. These are: (1) the extreme population I, containing the type II supernovae and massive main sequence stars, believed to be represented by the galactic CO distribution [Burton and Gordon, 1978] and (2) the total galactic visual luminosity, [Bahcall and Soneira, 1980] believed representative of novae [Ciardullo, 1984] and red giants. Both of these distributions fit the observations reasonably well, and cannot be distinguished with

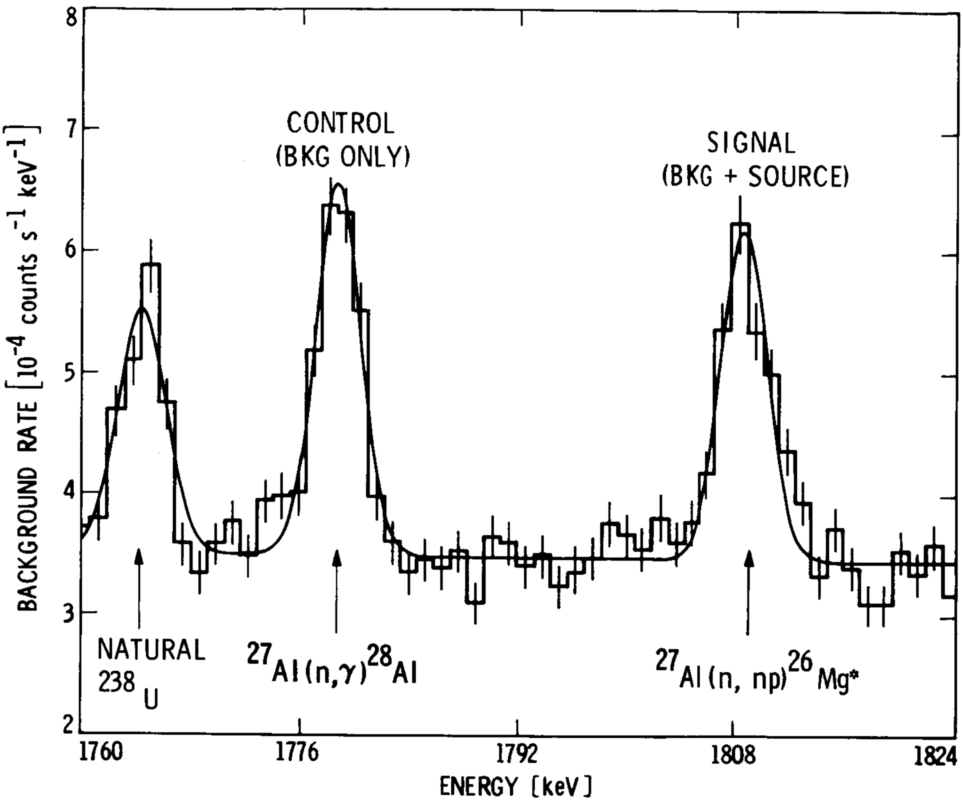

Figure 1. The background spectrum in the vicinity of the 1809 keV line. These lines are traceable in the main to either natural radioactive impurities, or emissions resulting from interactions by cosmic ray produced neutrons with the instrument and spacecraft materials.

the data. A brief study has been made of other source distributions. However, the statistical significance of these fits is such that the only distributions which can reasonably be ruled out are those which are very highly peaked toward the galactic center with full width at half maximum of less than about 6 degrees. The flux value from the direction of the galactic center depends upon the

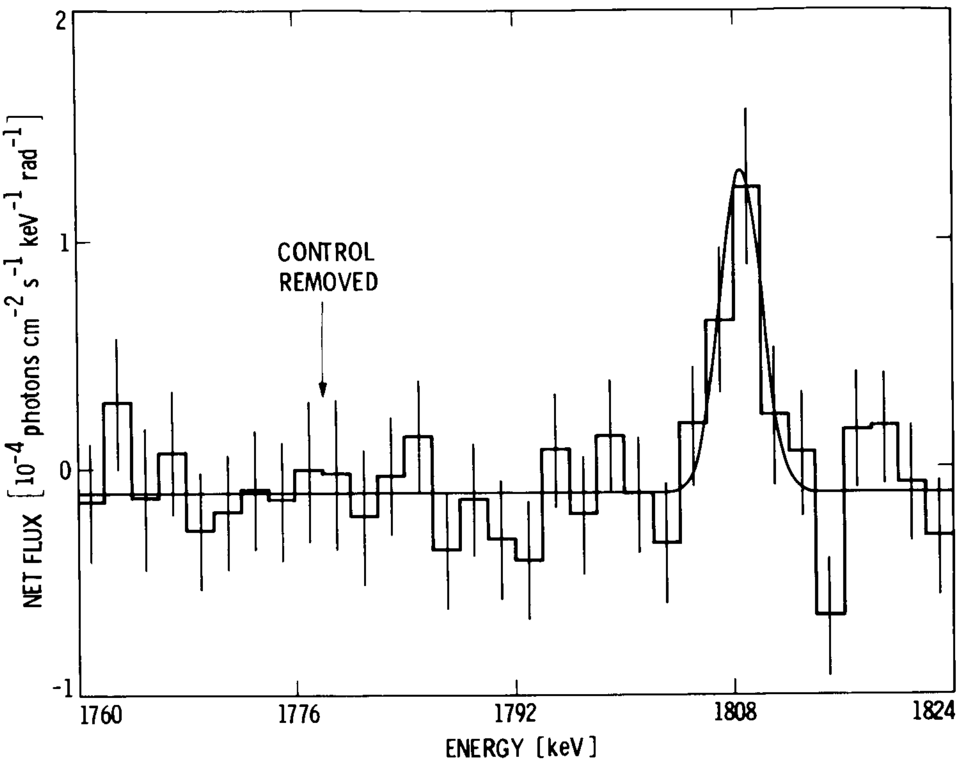

Figure 2. The net diffuse galactic gamma ray flux near 1809 keV. The process of analysis has eliminated the background lines and revealed the net cosmic component of the 1809 keV line.

distribution chosen, but for distributions which are statistically acceptable, the statistical significance of the line varies little.

In order to determine whether the peak of the distribution of ^{26}Al gamma rays is in the direction of the galactic center or some other direction indicating perhaps a local origin, fits of the extreme population I distribution were made to the data assuming the centroid of the distribution to be successively at longitudes spaced by 60 degrees around the galactic disk. Figure 3 shows the results of these fits where the statistical significance of the net flux from the

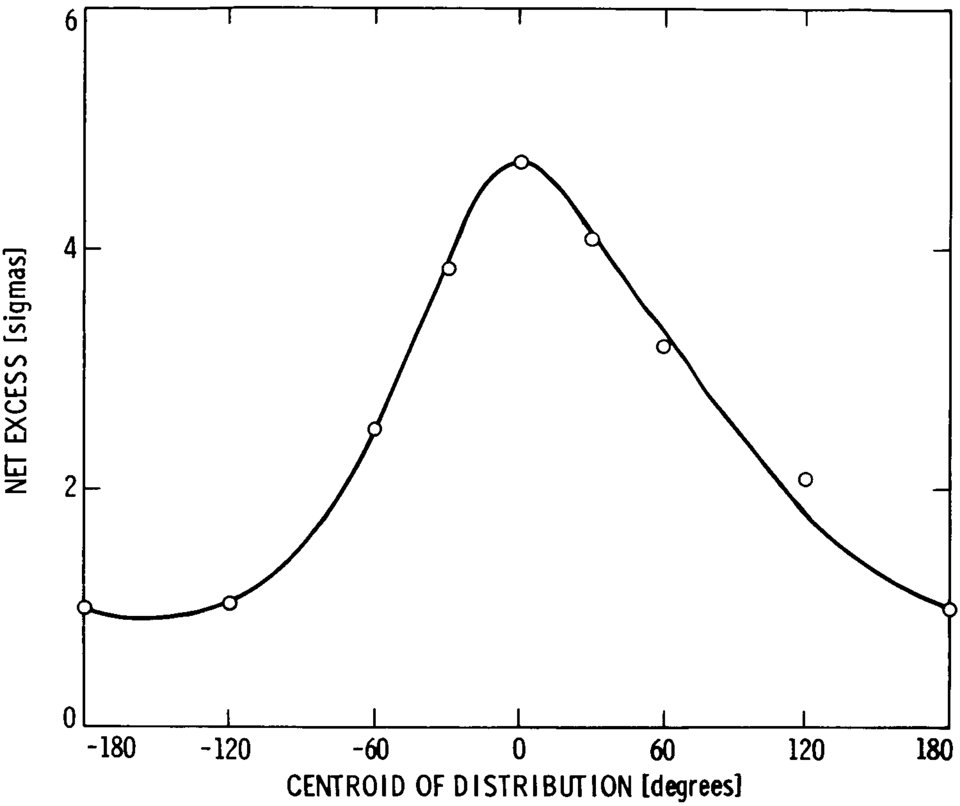

Figure 3. Significance of the 1809 keV observation as a function of galactic longitude.

direction of the centroid of the distribution is plotted against the centroid position. A similar study was carried out in galactic latitude. The net results of these studies shows that the emission is centered at $\ell = -6 \pm 22$ degrees and $b = -4 \pm 20$ degrees.

Share et al. [1985] have reported a confirming observation of the ^{26}Al galactic emission using the gamma ray detector aboard the Solar Maximum Mission satellite. In an analysis of 3.5 years of data, a net source of gamma ray line radiation was detected at an energy of 1804 ± 4 keV. Assuming a source distribution like that of the high energy gamma rays, they found a net flux from the direction of the galactic center of (4.0 ± 0.4) × 10^{-4} photons/cm^2-s-rad. The peak of the distribution was in an error box (99% confidence) defined by 345 and 25 degrees in galactic longitude and − 15 and + 10 degrees in latitude. These results agree in all respects with those of the HEAO-3 observations.

4. THE SOURCE OF THE ^{26}Al

An estimate of the total mass of ^{26}Al presently distributed in the galaxy can be arrived at in the following manner. It has been shown by Higdon and Lingenfelter [1976] that for a diffuse galactic gamma ray source with an extreme population I distribution, the measured flux, F, from the vicinity of the galactic center can be related to the total galactic luminosity, Q, by

$$F \text{ (photons/cm}^2\text{-s-rad)} = 1 \times 10^{-46}\ Q \text{ (photons/s)}.$$

Given the measured flux from the galactic center direction of F = 4.8 × 10^{-4} photons/cm^2-s-rad, it is found that the galactic luminosity in 1809 keV gamma rays is Q = 4.8 × 10^{42} photons/s. For a ^{26}Al mean lifetime of 1.04 × 10^6 years, the total mass of ^{26}Al presently in the galaxy is then about 3 M_O. A similar value for the mass of ^{26}Al is found under the assumption that the distribution follows the visual distribution model [Mahoney et al., 1985]. By taking the mass of the galactic interstellar medium to be 4 × 10^9 M_O [Salpeter, 1977] and the present average galactic mass fraction of ^{27}Al to be 6.6 × 10^5 [Cameron, 1982], we find that there is approximately 2.6 × 10^5 M_O of ^{27}Al in the galaxy. The present average galactic ration of $^{26}Al/^{27}Al$ is therefore about 1 × 10^{-5}.

Current models [Woosley and Weaver, 1980] indicate that supernova production is too low by at least an order of magnitude to explain the observed ^{26}Al [Clayton, 1984]. In novae, the production ratio of $^{26}Al/^{27}Al$ is approximately unity [Hillebrandt and Thielemann, 1982; Clayton, 1984], so that for a nova rate of 40 per year, an average ejected mass of about 10^{-4} M_O, and a ^{26}Al mass fraction in the ejecta of 2.6 × 10^{-4}, one can expect that there is about one solar mass of ^{26}Al from this process currently in the galaxy. This is the right order to account for the HEAO-3 observation. Hillebrandt and Thielemann [1982] have pointed out that the high productivity of novae in synthesizing ^{26}Al is rather insensitive to details of the nova model, but intimately reflects the properties of the nuclear reactions involved. Recent new results on the ^{26}Al production cross-sections will perhaps cause these estimates to be revised upward. Champaigne, Howard, and Parker [1983] have found one and perhaps two resonances in the cross section for the hydrogen burning reaction $^{25}Mg\ (p,\gamma)^{26}Al$, the main production reaction for ^{26}Al. These resonances tend to greatly increase the reaction rate at lower temperatures. These results require a reevaluation of the nova yields and open the possibilities for other stellar sources of ^{26}Al.

Norgaard [1980] has pointed out that significant amounts of ^{26}Al can be made at the base of the outer convective envelope in a red giant star. Cameron [1984] estimates that based upon the revised rate for $^{25}Mg\ (p,\gamma)\ ^{26}Al$, the case for this has been greatly strengthened and that a considerable fraction of the ^{25}Mg in the envelope of red giant stars may be converted to ^{26}Al. Pending a more precise calculation, he estimates that $^{26}Al/^{27}Al$ ratios of from unity to as much as 10 could occur and that if 0.1% or more of the interstellar medium has been recycled through red giant stars, then it is possible that the observed ^{26}Al may be principally contributed by them.

Blake and Dearborn [1984] and Dearborn and Blake [1985], have pointed out that type O and Wolf-Rayet stars will produce substantial amounts of ^{26}Al, and disperse the material in their intense stellar winds. They estimate that 0.5 M_O of ^{26}Al in the interstellar medium is traceable to this source.

In addition to the provocative theoretical work on the problems of nucleosynthesis, much interest in the production of ^{26}Al has been stimulated by the discovery of its decay products in primitive solar system materials. The study of select inclusions in meteorites lead to conclusions that a significant amount of radioactive ^{26}Al was present in the solar nebula when condensation took place.

The discovery of anomalously high quantities of ^{26}Mg, the decay product of ^{26}Al in primitive solar system materials [Lee, Papanastassiou, and Wasserburg, 1977] provided the most important reason leading to speculation that the formation of the solar system was triggered by a supernova close enough to the protosolar nebula to induce it to collapse as well as inject ^{26}Al [Cameron and Truran, 1977]. As pointed out by Cameron [1984], none of the arguments previously advanced for this model seems very compelling today. The HEAO-3 discovery of relatively large amounts of ^{26}Al in the interstellar medium suggests that the meteoritic inclusions reflect either normal interstellar concentrations or a nearby production site of rather more common occurrence than a supernova.

5. FUTURE EXPERIMENTS

The statistical limitations on the observations made thus far leave quite a number of unanswered questions about the distribution of ^{26}Al, and the source or sources of this material. While theoretical work can provide suggestions for specific measurements, these questions can ultimately be addressed only by further observations. The spatial distribution must be mapped in detail both in galactic longitude and latitude. Even angular resolution of about 5 $\times$ 5 degrees and a flux sensitivity five times greater than that of the HEAO-3 experiment would allow discrimination between extreme population I, and an older disk population.

High spectral resolution will also be significant in determining the spatial distribution of ^{26}Al through the study of velocity dispersions. Energy resolution presently achievable with germanium detectors would allow measurements of Doppler broadening of about 1 keV FWHM, permitting study of velocity dispersions as small as ± 85 km/s. For instance, 30 percent of galactic intermediate population stars such as novae and red giants are in the galactic ellipsoidal bulge, concentrated toward the galactic nucleus [Higdon, 1985]. This population has a velocity dispersion of about 130 km/s. On the other hand, extreme population I stars concentrated in the disk have a velocity dispersion of about 30 km/s. Independent of angular resolution, improved spectral resolution and sensitivity will separate the galactic bulge and disk components of ^{26}Al. The portion of the ^{26}Al still exhibiting velocities associated with its production sites ($10^3 - 10^4$ km/s) and dispersion processes may also be observable.

The observations need to be extended to other products of nucleosynthesis. The immediate candidates are those shown in Table 1. The measurement of a galactic 511 keV line would serve as an indicator of explosive ^{56}Fe synthesis in type I supernovae. Positrons are produced in the decay of ^{56}Co and a fraction (perhaps 10%) are believed to escape from the expanding shell and annihilate in the interstellar medium over 10^5 to 10^6 years. Thus one could see a narrow line with an intensity comparable to the 1809 keV line. Its spatial distribution could also have important implications for the propagation and acceleration of cosmic rays. Analysis of this component is underway at present in the HEAO-3 data. The measurement of the decay lines of ^{60}Fe would demonstrate ongoing nucleosynthesis in massive young stars via helium burning in type II supernovae. The lines are also expected to be narrow with an intensity of order 10% that of the 1809 keV line. Measurement of the spatial distribution would indicate regions of massive star formation in the galaxy. The isotope ^{44}Ti is produced in type I supernovae (SN I). The measurement of line emission from this isotope would identify recent (of order 100 years) and previously known SN I remnants in the galaxy.

For the reasons given above, high resolution spectroscopy is an important part of any gamma ray astronomy program. At this time, however, there is no high resolution spectroscopy experiment currently planned for a space mission. There was originally a high resolution gamma ray spectrometer as part of the payload of the Gamma Ray Observatory (GRO) to be launched in 1988. For budgetary reasons, NASA decided to remove this experiment from the complement of instruments, rationalizing that the low resolution scintillation spectrometer aboard the mission could satisfy the spectroscopic objectives of low energy gamma ray astronomy. This design was made before many of the current discoveries in this spectral region. It was based in part on an expectation that narrow gamma ray lines would not be seen. In fact, at that time the only confirmed and well established extra-solar system line, the galactic center .511 MeV line *was* narrow. With the possible exception of lines in gamma ray bursts and solar flares, only narrow lines have been observed thus far. The width of these lines is crucial to the understanding of their sources. The narrow width ($\lesssim$ 3 keV) of the galactic center line sets important limits on the gravitational potential, temperature, and degree of ionization of the positron-electron annihilation medium [Leventhal, MacCallum, and Stang, 1978; Riegler et al., 1981; Riegler et al., 1985]. Thus, the failure to include a high spectral resolution instrument in the present program was, in retrospect, unfortunate.

Scintillation spectrometers such as the one presently in the GRO payload, with spectral resolution some 25 or more times worse than germanium spectrometers, have made valuable contributions to the field of gamma ray spectroscopy, notably in the areas of solar flare [see Chupp, 1982 and Chupp, 1984] and gamma ray burst [Mazets et al., 1981] measurements. In these observations, the fluxes have been large compared to the detector background, and the duration of the observations has been short so that systematic effects become less important. However, even in these types of observations, the relatively poor spectral resolution has limited the degree to which line width measurements can characterize the emission regions. Additionally, if the spectra are highly complex, as in the case of some of the solar flares, the identification of the components becomes difficult or impossible.

There are other factors beside the spectral resolution which seriously limit the ability of scintillation detectors to make long duration observations under low signal-to-background conditions, regardless of whether narrow or broad gamma ray lines are expected. Both types of instruments, their structural materials, and their vehicles are subject to cosmic ray bombardment which initiates nuclear reactions. These reactions result in numerous gamma ray lines in the background. Figure 4 shows the background as measured by the HEAO-3 high resolution gamma ray spectrometer. There are more than 140 lines, each exhibiting characteristic time variation as the spacecraft executes its various orbital motions, passages through the South Atlantic Anomaly, or continues to be exposed to the ambient radiation environment. While the details of which lines are present, and what their intensities and time variations may be, both germanium and scintillation detectors, and any other materials used in these instruments have backgrounds of similar complexity.

The ability to deal with this systematic background and compensate for it depends upon the experimenter's ability to detect, identify, and characterize each component. The high resolution of germanium allows identification of

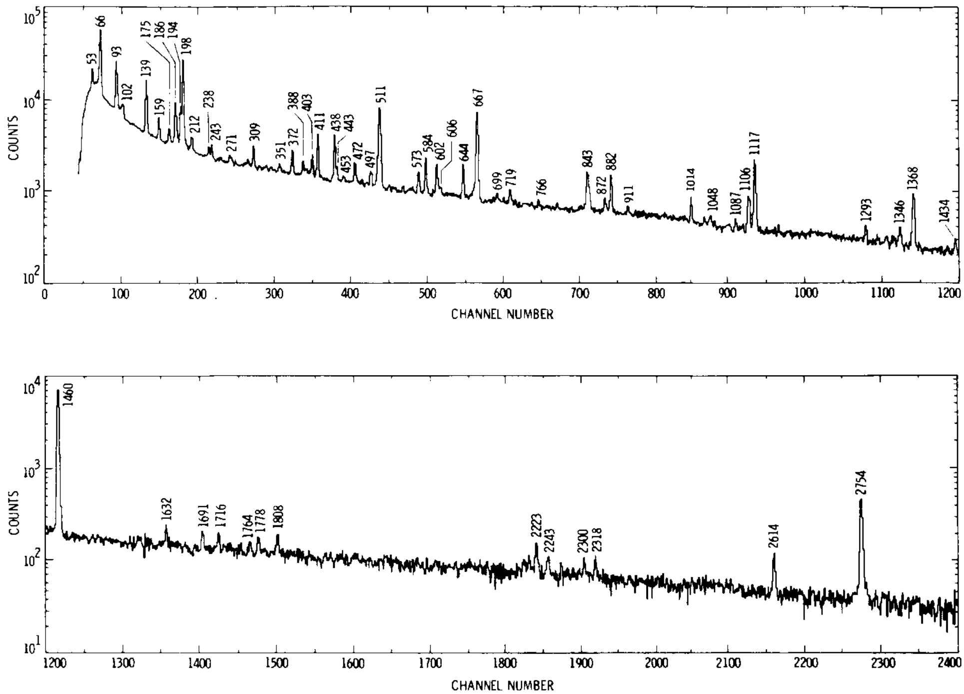

Figure 4. A background spectrum measured in one of the HEAO-3 detectors. The spectrum represents a four-day accumulation.

most of the lines and hence the characteristic of their sources. With scintillation detectors, such identifications are largely guess work. This introduces large systematic errors which are extremely difficult to deal with and hence often overlooked when reporting the results of measurements.

The history of non-solar gamma ray spectroscopy with scintillators also suggests a cautious attitude about the expectations of the GRO low energy gamma ray detector to make low intensity spectroscopic measurements. Several expeditions to the Southern Hemisphere to observe the galactic center with a scintillation spectrometer did yield positive measurements of a line near .511 MeV [Johnson and Haymes, 1973; Haymes et al., 1975] but never close enough to the energy .511 MeV to be convincingly identified as positron-electron annihilation radiation. Not until observations with germanium spectrometers began [Leventhal, MacCallum, and Stang, 1978] was it established that in the direction of the galactic center there was a source of positron-electron annihilation radiation.

A situation paralleling the original GRO project existed in the HEAO program, which included *both* scintillation and germanium spectrometers. Reviewing the results obtained by these experiments to date, it is striking how little overlap there has been. In particular, essentially none of the narrow line results from the HEAO high resolution spectrometer have been accessible to the HEAO-1 scintillation spectrometer. The reason is that NaI and Ge spectrometers have very different capabilities, making them complementary rather than competitive. Because NaI is cheaper than high purity Ge, and does not require cooling to cryogenic temperatures, a scintillation experiment will be cheaper and simpler per square centimeter of effective area than a high resolution spectrometer of similar proportions. But scintillators simply cannot address whole areas of astronomical observation which are accessible to Ge. It is extremely difficult in practice for scintillation instruments to convincingly demonstrate the existence of weak lines, as is shown by the HEAO program experience with the 511 keV and 1809 keV lines. When one move beyond mere existence to ask questions about the energy, width, and profile of these lines, in which a great richness of astrophysical information is contained, "extremely difficult in practice" becomes "obviously impossible". Because there is no high resolution spectrometry experiment on the GRO, such questions will probably not be answered in the next five years.

To do the necessary and comprehensive job of observationally establishing the source of the ^{26}Al and to extend these observations to other products and processes of nucleosynthesis requires the development and space flight of a high resolution gamma ray spectrometer. Specifically, space flight rather than balloon flights are needed because the latter, while providing a somewhat more benign environment with regard to sources of systematic error, drastically limit: (1) the number of sources available in a reasonable time for study, (2) the observing time achievable upon any single source, and (3) the studies which can be made of large-scale diffuse sources. An impractically large number of balloon flights would be required to adequately address these subjects. It is a sobering thought that the usable observing time of the HEAO-3 gamma ray spectrometer was longer than the combined observing time of all the gamma ray astronomy balloon flights ever made.

Recent missions have tended to be large and consequently expensive observatories. Because of the expense, the frequency of mission opportunities has been reduced. The likelihood of on-orbit servicing and repair of satellite payloads could extend the lifetimes of these observatories and contribute further to the scarcity of opportunities to launch a large and definitive high resolution spectrometer, so that a decade or more could elapse before the important measurements discussed above are carried out. I believe that every effort should be made by interested scientists and by NASA to see that an opportunity to fly a high resolution gamma ray spectrometer occurs in the near future.

6. SUMMARY

The HEAO-3 gamma ray spectrometer has provided new evidence in the quest for the understanding of complex element formation in the universe with the discovery of ^{26}Al in the interstellar medium. It has demonstrated that the synthesis of intermediate mass nuclei is currently going on in the galaxy. This discovery has been confirmed by the Solar Maximum Mission. The flux is peaked near the galactic center and indicates about 3 $M_\odot$ of ^{26}Al in the interstellar medium, with an implied ratio of $^{26}Al/^{27}Al = 1 \times 10^{-5}$. Several possible distributions have been studied but the data gathered thus far do not allow discrimination between them. It is felt that only the spaceflight of a high resolution gamma ray spectrometer with adequate sensitivity will ultimately resolve the issue of the source of this material.

The author wishes to acknowledge valuable suggestions by his colleagues, J. C. Higdon, J. C. Ling, W. A. Mahoney, R. A. Schwartz, and Wm. A. Wheaton.

REFERENCES

Bahcall, J. N., and Soneira, R. M., 1980, *Astrophys. J.* (Suppl.), **44**, 73.

Blake, J. B., and Dearborn, D. S. P., 1984, *Adv. Space Res.*, **4**, 89.

Burbidge, G. R., Hoyle, F., Burbidge, E. M., Christy, R. F., and Fowler, W. A., 1956, *Phys. Rev.*, **103**, 1145.

Burton, W. B., and Gordon, M. A., 1978, *Astrophys. J.*, **63**, 7.

Cameron, A. G. W., 1982, in *Essays in Nuclear Astrophysics*, ed. C. A. Barnes, D. D. Clayton, and D. N. Schramm (Cambridge University Press), p. 23.

Cameron, A. G. W., 1984, *Icarus*, **60**, 416.

Cameron, A. G. W., and Truran, J. W., 1977, *Icarus*, **30**, 447.

Champaigne, A. E., Howard, A. J., and Parker, P. D., 1983, *Astrophys. J.*, **269**, 686.

Chupp, E. L., 1982, in *Gamma-Ray Transients and Related Astrophysical Phenomena*, ed. R. E. Lingenfelter, H. S. Hudson, and D. M. Worrall (New York: A.I.P.), p. 363.

Chupp, E. L., 1984, *Ann. Review of Astron. and Astrophysics*, **22**, 359.

Ciardullo, R., 1984, *BAAS*, **16**, 977 and 1985, private communication.

Clayton, D. D., 1974, *Astrophys. J.*, **188**, 155.

Clayton, D. D., 1975, *Astrophys. J.*, **198**, 151.

Clayton, D. D., 1982, *J. R. Astr. Soc.*, **23**, 1974.

Clayton, D. D., 1984, *Astrophys. J.*, **280**, 144.

Clayton, D. D., Colgate, S. A., and Fishman, G. J., 1969, *Astrophys. J.*, **155**, 75.

Clayton, D. D., and Craddock, W. L., 1965, *Astrophys. J.*, **142**, 189.

Clayton, D. D., and Hoyle, F., 1974, *Astrophys. J.*, **187**, L101.

Clayton, D. D., and Hoyle, F., 1976, *Astrophys. J.*, **203**, 490.

Dearborn, D. S., and Blake, J. B., 1985, *Astrophys. J.*, **288**, L21.

Haymes, R. C., Walraven, G. D., Meegan, C. A., Hall, R. D., Djuth, F. T., and Shelton, D. M., 1975, *Astrophys. J.*, **201**, 593.

Higdon, J. C., 1985, private communication.

Higdon, J. C., and Lingenfelter, R. E., 1976, *Astrophys. J.*, **208**, L107.

Hillebrandt, W., and Thielemann, F. K., 1982, *Astrophys. J.*, **255**, 617.

Jacobson, A. S. "A Search for Gamma-Ray Line Emissions from the Crab Nebula." Ph.D. dissertation, University of California, San Diego, 1968.

Johnson, W. M., and Haymes, R. C., 1973, *Astrophys. J.*, **184**, 203.

Lee, T., Papanastassiou, D. A., and Wasserburg, G. J., 1977, *Astrophys. J.*, **221**, L107.

Leventhal, M., MacCallum, C. J., and Stang, P. D., 1978, *Astrophys. J.*, **225**, L1.

Lingenfelter, R. E., and Ramaty, R., 1978, *Physics Today*, **31**, 40.

Mahoney, W. A., Ling, J. C., Jacobson, A. S., and Lingenfelter, R. E., 1982, *Astrophys. J.*, **262**, 742.

Mahoney, W. A., Ling, J. C., Jacobson, A. S., and Tapphorn, R. N., 1980, *Nucl. Inst. & Methods*, **178**, 363.

Mahoney, W. A., Higdon, J. C., Ling, J. C., Wheaton, W. A., and Jacobson, A. S., 1985, *19th Internat. Cosmic Ray Conference Papers (La Jolla)*, **1**, 357.

Mahoney, W. A., Ling, J. C., Wheaton, W. A., and Jacobson, A. S., 1984, *Astrophys. J.*, **286**, 578.

Mazets, E. P., Golenetskii, S. V., Aptekar, R. L., Gur'yan, Y. A., and Il'inskii, V. N., 1981, *Nature*, **290**, 378.

Morrison, P., 1958, *Il Nuovo Cimento*, **7**, 858.

Norgaard, H., 1980, *Astrophys. J.*, **236**, 895.

Ramaty, R., and Lingenfelter, R. E., 1977, *Astrophys. J.*, **213**, L5.

Riegler, G. R., Ling, J. C., Mahoney, W. A., Wheaton, W. A., and Jacobson, A. S., 1985, *Astrophys. J.*, **294**, L13.

Riegler, G. R., Ling, J. C., Mahoney, W. A., Wheaton, W. A., Willett, J. B., and Jacobson, A. S., 1981, *Astrophys. J.*, **248**, L13.

Salpeter, E. E., 1977, *Ann. Rev. Astr. Ap.*, **15**, 267.

Savedoff, M. P., 1959, *Il Nuovo Cimento*, **13**, 1584.

Share, G. H., Kinzer, R. L., Kurfess, J. D., Forrest, D. J., Chupp, E. L., and Rieger, E., 1985, *Astrophys. J.*, **292**, L61.

Wheaton, W. A., Ling, J. C., Mahoney, W. A., and Jacobson, A. S., 1987, to be submitted to *Astrophys. J.*

Woosley, S. E., and Weaver, T. A., 1980, *Astrophys. J.*, **238**, 1017.