5-15-1988

Gamma-Ray Limits on Na-22 Production in Novae

Mark D. Leising
Clemson University, lmark@clemson.edu

Gerald H. Share
Naval Research Lab

Edward L. Chupp
University of New Hampshire

Gottfried Kanbach
Max Planck Institute for Physics and Astrophysics

Recommended Citation

Please use publisher's recommended citation.

1988ApJ...328..755L

THE ASTROPHYSICAL JOURNAL, **328**:755–762, 1988 May 15

GAMMA-RAY LIMITS ON ^{22}Na PRODUCTION IN NOVAE

MARK D. LEISING[1] AND GERALD H. SHARE
E. O. Hulburt Center for Space Research, Naval Research Laboratory
EDWARD L. CHUPP
University of New Hampshire
AND
GOTTFRIED KANBACH
Max Planck Institute for Physics and Astrophysics, Institute for Extraterrestrial Physics
Received 1987 September 28; accepted 1987 November 9

ABSTRACT

Data accumulated from 1980 to 1987 by the gamma-ray spectrometer on NASA's *Solar Maximum Mission* have been searched for evidence of cosmic line emission at 1.275 MeV. This emission would result from the decay of ^{22}Na, which might be produced in the proton-rich thermonuclear explosions thought to characterize classical nova outbursts. No evidence of any 1.275 MeV emission of celestial origin has been found. A limit of $3 \times 10^{-6}\ M_\odot$ is placed on the accumulated ^{22}Na from many novae occurring near the Galactic center, and a limit of $7 \times 10^{-7}\ M_\odot$ is placed on the mass of ^{22}Na ejected by the closest of the recent neon-rich novae. These limits, while lower than any previous ones, are not in conflict with recent theoretical predictions of the production of ^{22}Na in novae. The product of the frequency and average initial neon abundance of novae of the neon-rich class is constrained by the Galactic center ^{22}Na limit.

Subject headings: gamma rays: general — nucleosynthesis — stars: abundances — stars: novae

I. INTRODUCTION

The classical nova outburst has been modeled as a thermonuclear runaway in the accreted hydrogen-rich envelope of a white dwarf (e.g., Starrfield, Sparks, and Truran 1974; Starrfield, Truran, and Sparks 1978). In general, observations of novae support such models (Gallagher and Starrfield 1978; Truran 1982). In the hot nuclear burning, repeated proton captures produce many unstable nuclei. Those with decay lifetimes long enough to survive until the expanding ejecta in which they reside becomes thin to gamma rays might be directly observed via their decay photons. The nova ejecta would be completely transparent to gamma rays within a few days after outburst. Observations of these gamma-ray lines would not only confirm the mechanism of the nova phenomenon, but also provide important boundary conditions on models of nova dynamics and nucleosynthesis.

Clayton and Hoyle (1974) proposed that ^{22}Na might be produced in substantial quantities from proton captures on neon initially present in the nova atmosphere. Sodium 22 decays (90% β^+ emission; 10% β^- capture) to a short-lived excited state of ^{22}Ne at 1.275 MeV. If produced in sufficient quantities, ^{22}Na could be detected in the accumulated debris of many (of order 100) novae which are thought to occur in the central region of the Galaxy during its mean lifetime of 3.75 yr. It might also be detected in the ejecta of individual novae which occur within a few kiloparsecs of the Sun, especially those observed to have large abundances of neon and heavier elements.

The *Solar Maximum Mission* (*SMM*) spacecraft is always pointed at the Sun and so scans the ecliptic annually. Thus the gamma-ray spectrometer (GRS) on board can detect a persistent source of gamma rays via an increase in the counting rate for a few months of the year as a source transits its wide field of view. Galactic gamma-ray line emissions at 1.809 and 0.511 MeV have been detected since 1980 as annual increases in the GRS counting rates at those energies during Galactic center transits of the GRS field of view (Share *et al.* 1985; Share *et al.* 1988). We employ similar data analysis techniques to search for annual increases at 1.275 MeV as evidence of ^{22}Na decay in the Galactic center region and in the ejecta of recent individual novae.

II. DATA ANALYSIS

The *SMM* GRS instrument and data analysis techniques have been recently described by Share *et al.* (1988) and the instrument was described in detail by Forrest *et al.* (1980). It has been operating continuously since 1980 except for one 5 month period in 1983–1984. The GRS has an effective area of 100 cm^2 for detecting a line at 1.275 MeV from a source lying on the detector axis. To calculate its response to a celestial source, we approximate the angular response of the instrument (which was not measured) at that energy with a Gaussian of width 130° FWHM, with a constant 10% leakage at large angles to the detector axis. Since this analysis was completed, a Monte Carlo simulation of the instrument response has been performed (Matz and Jung 1987). Using the response given by that calculation instead of the Gaussian function assumed here does not significantly affect our results. The GRS energy resolution at 1.275 MeV is 75 keV FWHM, or about 6%.

The data base we use is essentially identical to that used and described by Share *et al.* (1988). In short, data are selected for quality from 1 minute spectral summations and then summed over 3 day intervals according to three parameters: time since traversal of the South Atlantic Anomaly, geomagnetic rigidity, and the angle between the detector axis and the direction to the center of the Earth (Earth angle). The subset of the data we analyze is then formed by summing, for each 3 day period since

---

[1] Resident Research Associate at the Naval Research Laboratory, under the NRC Associateship Program.

1988ApJ...328..755L

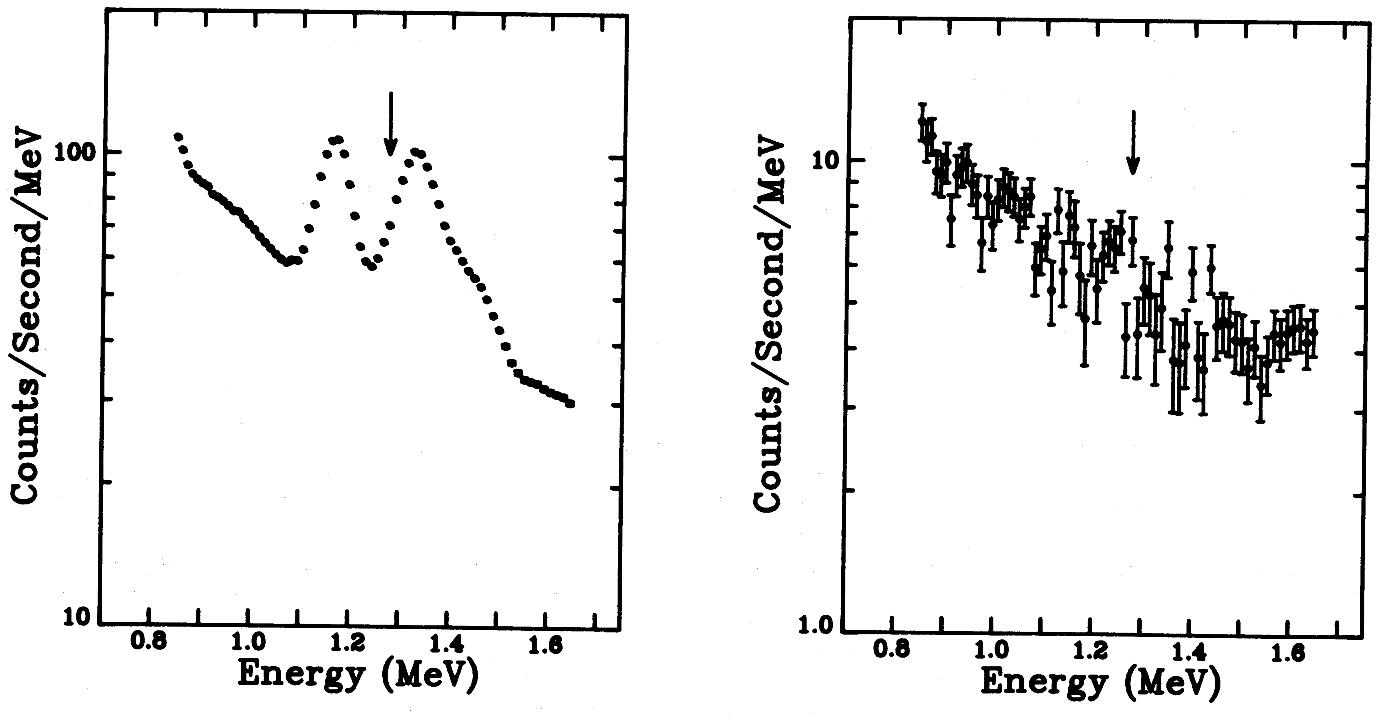
the start of the mission, data of all geomagnetic rigidity which were accumulated at least 10^4 s after the most recent traversal of the South Atlantic Anomaly, into two spectra distinguished by Earth angle. One, which we refer to as "sky-viewing," is accumulated when the angle between the spacecraft axis and the spacecraft–Earth center vector is between 108° and 252°. The other, "Earth-viewing," is accumulated when the Earth angle is between 288° and 72°. Any potential source near the center of the GRS field of view will be largely occulted in Earth-viewing data and unocculted in sky-viewing data. We thus have some 800 sets of two spectra in which to search for variations indicative of a celestial source of emission. Typically, the live times of the 3 day sky-viewing spectra are 2.5×10^4 s, while those of the Earth-viewing spectra are 1.7×10^4 s (instrument calibration is performed when the earth is in view).

A typical sky-viewing spectrum accumulated over 3 days in the energy region of interest is shown in Figure 1*a*. The line features which are evident are instrumental. The most prominent lines, at 1.17 and 1.33 MeV, are from ^{60}Co, a calibration source in the instrument. There are other line features blended with these, most of which result from radioactive nuclei produced by particle irradiation of the instrument. Among these is a line at 1.275 MeV from the decay of ^{22}Na produced by the spallation of aluminum in the detector housing. This feature complicates the search for celestial emission at this energy. However, if the overall time variations of the line intensity can be understood and modeled, then an additional time variation, such as that expected from a celestial source, can in principle be identified.

We find that the spectra from 0.9 to 1.6 MeV can be fitted reasonably well by a continuum, approximated by a cubic polynomial, plus six Gaussian lines superposed on it. All six lines, at energies determined by the fitting routine, are required to obtain the best fit. In addition to the three line energies mentioned above, we also fit lines at 1.37, 1.43, and 1.46 MeV. The first two of these probably result from ^{24}Na and ^{52}Mn, respectively, produced in the instrument. The 1.46 MeV feature, which shows a radioactive buildup over the first 3–4 weeks of the mission, is as yet unidentified. In the final fit, the line energies are allowed to vary within about 20 keV of the expected values (obtained from preliminary fits), and the line widths are allowed to vary only slightly from the instrumental resolution at that particular energy. In the case of the 1.275 MeV line, this range in width is large enough to include the broadening due to 3000 km s^{-1} radial expansion of nova-ejected material. Thus we obtain the best overall fits in the ~800 source spectra accumulated over the course of the mission.

The time profiles of the intensities of the lines (other than the 1.46 MeV feature) are consistent with the above identifications. The 1.17 and 1.33 MeV line intensities simply decay exponentially in time as expected from the ^{60}Co calibration source. The intensities of the lines at 1.37 and 1.43 MeV show roughly the same time variations as other relatively short-lived background features (see Share *et al.* 1988). They reveal long-term trends due to the decreasing satellite altitude and approaching solar minimum and a ~47 day periodicity associated with the precession of the satellite orbit.

The time variation of the fitted 1.275 MeV line intensity is shown in Figure 2, where the data are summed, weighted by the errors, to 24 days for presentation purposes. There are no obvious local maxima recurring annually. The overall varia-



a)

b)

FIG. 1.—Spectra accumulated in a randomly chosen 3 day interval, for the energy range of interest. (*a*) Sky-viewing data. Error bars are included. (Earth-viewing data minus sky-viewing data. The arrow marks energy 1.275 MeV.

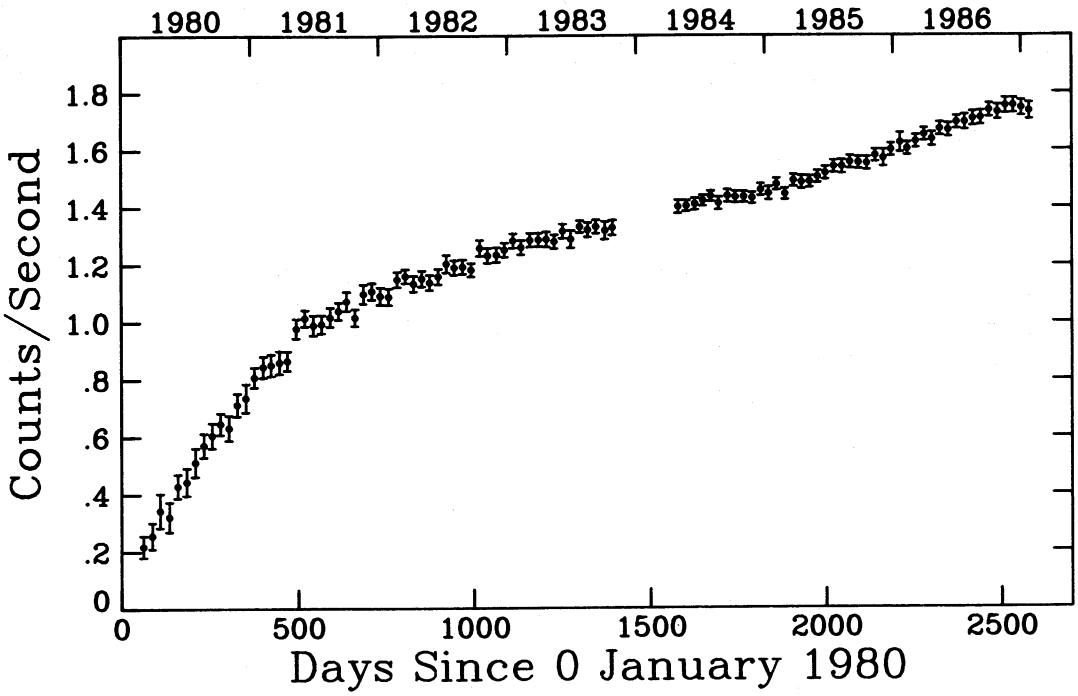


FIG. 2.—The GRS count rate in a line at 1.275 MeV as a function of time, summed to 24 days, in sky-viewing data.

tion is satisfactorily explained by a two-parameter model, where the measured 1.275 line intensity is taken to result from the radioactive decay of a nucleus which is produced in proportion to the radiation dosage of the instrument (as given by the measured intensity of a line, in this case at 0.67 MeV). (This feature probably results from the decay of short-lived nuclei, ^{132}Cs and ^{126}I, with mean lifetimes 9.4 and 18.6 days, respectively.) Allowing the radioactive lifetime and the constant of proportionality to be free parameters, the best fit to the data is obtained for a mean radioactive lifetime of 3.75 ± 0.11 yr, in agreement with the ^{22}Na lifetime. The data require no additional source of 1.275 MeV emission. It is remarkable that this feature can be understood as well as it can, given its position in such a complicated spectral region (see Fig. 1*a*).

We can improve our sensitivity by subtracting these instrumental background features. For each 3 day period the sky-viewing spectrum is subtracted from the Earth-viewing spectrum. What results is essentially an atmospheric gamma-ray spectrum (a typical subtraction of 3 day accumulations is shown, for the energy range of interest, in Fig. 1*b*). Any celestial lines would appear as depressions relative to the atmospheric spectrum. The instrumental lines, including the feature at 1.275 MeV, are in most cases removed. Each of these ~800 difference spectra are fitted with a power-law continuum and from one to five lines, as mentioned above. None of the lines are found to be present with any high degree of significance. The results quoted here are from those fits performed with only one line, at 1.275 MeV, but the results for that line do not change appreciably when others are included. The energy of the line is held fixed and the width is allowed to vary from the instrumental resolution to 79 keV FWHM, which is that expected from passing a line intrinsically broadened by 3000 km s^{-1} through the instrument. The fitted intensity of the 1.275 MeV line over the course of the mission is displayed, summed to 24 days, in Figure 3. Also shown in that figure is the expected response to a Galactic center source with intensity equal to that of the measured 1.809 MeV flux from ^{26}Al, whose production might be related to ^{22}Na production (see below). Both the data and the simulated count rate are displayed with source contribution in a positive sense. There are no apparent variations of the intensity such as are expected from a celestial source. The data are consistent with zero celestial 1.275 MeV line emission.

In order to determine what the sensitivity of this search is to a particular source, we model how the counting rate in the instrument would vary with time due to a flux from that source. Variations are caused by the passage of a source through the GRS field of view, the occultation of the source by the Earth, and intrinsic source variation (the 3.75 yr decay, in the case of an individual nova). In determining the upper limits on the flux from a particular source, we make the assumption that there are no other sources, that is, the limit on each source is determined independently. As the contributions from all sources are obviously small, this assumption should not greatly affect the resulting limits for any particular source. In Figure 4 we plot the expected variation of the GRS counting rate for a particular source, Nova Aquilae 1982, again summed over 24 day intervals. The function is normalized to unity at the counting rate at the time of the outburst, for a source lying on the detector axis and occulted by the Earth in all Earth-viewing spectra and unocculted in all sky-viewing spectra. Of course, these conditions are not met for most sources, so the function does not reach unity. Similar functions are computed for each of several other recent novae and for a constant accumulated Galactic source (see Fig. 3).

Each of the models of the sources was fitted to the data, in a two-parameter fit. The amplitude of the source flux and the zero level, or constant (in time) background, were allowed to vary until the best fit was obtained. No model was found to have an intensity more significant than one standard deviation (1 σ), nor was the deviation of the constant background from zero more significant than 1 σ. The limits reported in Table 1 were then obtained by fixing the intensity of the model at

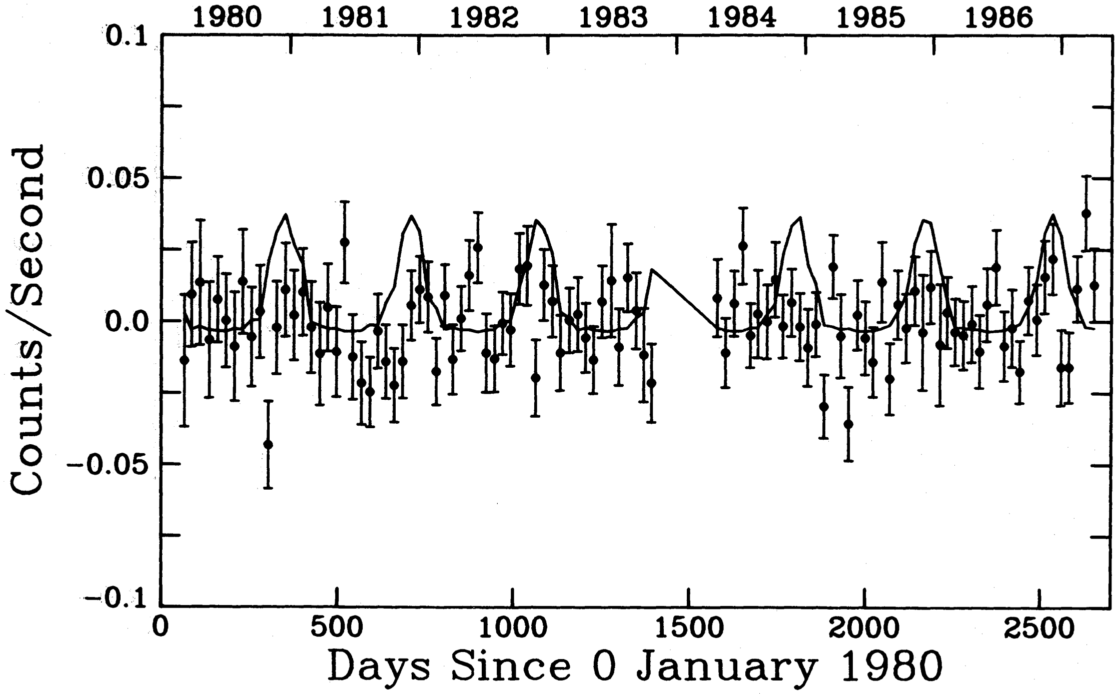


FIG. 3.—The count rate in a line at 1.275 MeV as a function of time, summed to 24 days, in background subtracted data. The data is displayed so that a source in sky-viewing data would produce a positive count rate. The solid line is the GRS response to a Galactic center flux of 4.0 × 10^{-4} photons $\mathrm{cm}^{-2}\ \mathrm{s}^{-1}$, equivalent to the measured 1.809 MeV line intensity from ^{26}Al. This intensity is also comparable to the *HEAO 3* 1.275 MeV line upper limit.

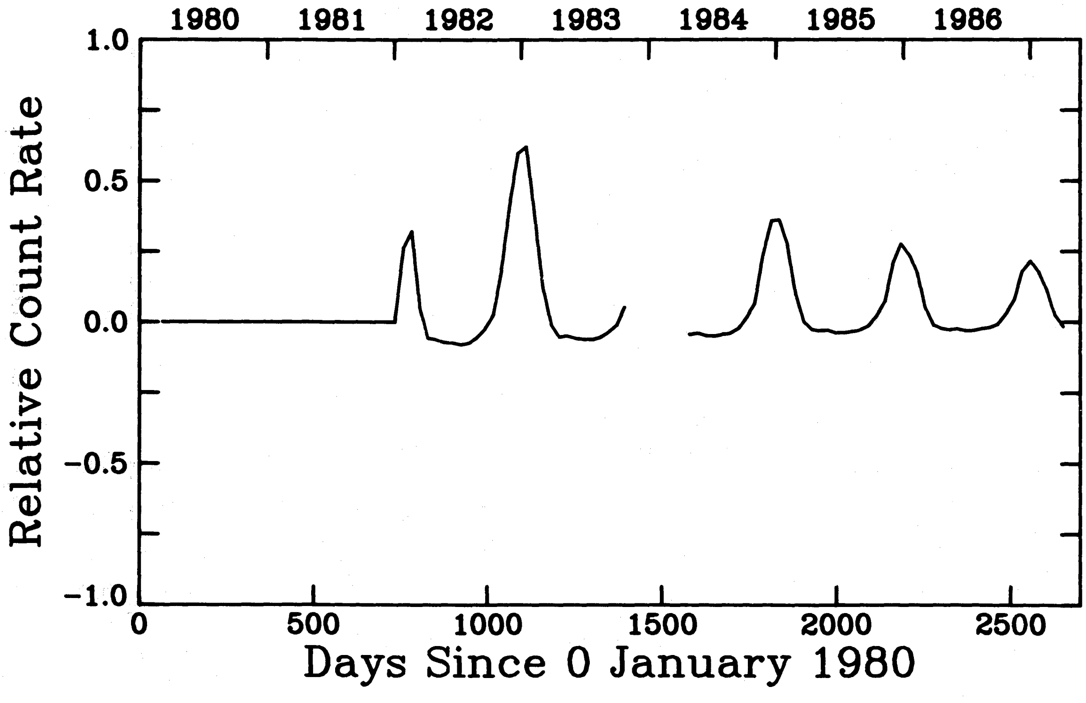


FIG. 4.—The expected variation of the background-subtracted GRS count rate due to a source which decays with lifetime 3.75 yr, at the position of Nova Aquilae 1982. The function is normalized to unity for a source at outburst which lay on the detector axis and was entirely unocculted in sky-viewing data and occulted in Earth-viewing data.

TABLE 1

LIMITS ON 1.275 MeV GAMMA-RAY LINE EMISSION

	Galactic Center	N Cyg 1975	N CrA 1981	N Aql 1982	N Vul 1984#2	Sum of Four Novae
Flux limit[a]	1.2	25	3.2	2.5	3.0	...
^{22}Na mass limit[b]	3.1	1.5	8.6	1.6	0.7	0.5[c]

[a] Flux implied at outburst for individual novae, assumed constant for Galactic center; limits are 99% confidence level; units are 10^{-4} photons cm^{-2} s^{-1}.

[b] At distances given in text; units are 10^{-6} $M_\odot$.

[c] Assuming equal ^{22}Na mass produced in each.

increasing values until the χ^2 statistic varied from its best-fit value by an amount corresponding to the 99% level of confidence for a two-parameter model as given in Table 1 of Lampton, Margon, and Bowyer (1976). Because other factors such as source exposure, instrument response, and time between outburst and the observations are included in the models, the stated flux limits represent the gamma-ray flux at the time of outburst and can be translated directly into ejected mass of ^{22}Na (also listed in Table 1), given a distance to the source.

III. RESULTS AND DISCUSSION

The translation of gamma-ray flux limits into meaningful limits on the production of ^{22}Na in novae—objects often unobserved and revealing little uniformity when they are observed—is subject to much interpretation. The frequencies and distributions of the various types of nova events are highly uncertain. Even relatively well-observed novae are subject to uncertainties of factors of 2 in distance. There are thought to be two components of the Galactic distribution of novae, those associated with the disk, and those associated with the spheroid or bulge. Disk novae in proximity to the Sun can be observed, so we have limited knowledge of their distribution and frequency (Kopylov 1955; Patterson 1984). Only a few observed novae can perhaps be associated with the Galactic spheroidal component, those far enough from the plane so that they are not visually obscured by the disk. The idea that a large number of novae occur there is postulated from observations of other galaxies, and their distribution and rate of occurrence can only be inferred from those observations. Some authors have discussed the characteristics of Galactic novae inferred from observations of novae in M31, the best observed extragalactic system of novae.

For the question of ^{22}Na gamma-ray emission the two populations are inherently different. The density of bulge novae in M31 follows closely the stellar luminosity density (Ciardullo *et al.* 1987) which is strongly peaked toward the nucleus. In the Galaxy, such a distribution would appear as a nearly constant, pointlike source of 1.275 MeV emission to a large–field-of-view gamma-ray detector, if the novae rate is greater than a few per year. Novae in the disk, however, are spread over a much larger area, and unless their frequency is very great indeed, the ^{22}Na gamma-ray flux would appear patchy in space and time. This has been demonstrated for a reasonable distribution and frequency by Higdon and Fowler (1987). We will set limits on ^{22}Na production for those disk novae which have been actually observed, but will make no conjecture about others undiscovered because of visual obscuration.

Complicating matters further is the recent recognition of a distinct class of nova events, those which eject matter extremely rich in neon. Early estimates (e.g., Clayton and Hoyle 1974) of ^{22}Na production had to be revised downward by several orders of magnitude because of revisions in nuclear cross sections (Wallace and Woosley 1981). However, observations of novae with neon (the seed for ^{22}Na production) abundances perhaps 100 times greater than standard solar abundances revived the possibility of observing ^{22}Na from novae. Observations of a few of these novae are discussed below. The distribution and frequency of such novae are even more uncertain than those of the typical novae.

a) Diffuse Galactic Center Source

We considered two distributions of emission from the Galactic center region: a point source and the slightly extended distribution of Leising and Clayton (1985). The latter is based on historical observations of novae in M31 (Sharov 1971), where the spheroidal component of novae dominates the disk component. (Ciardullo *et al.* [1987] find that the luminosity-specific nova density in the bulge of M31 is at least 10 times that in the disk.) The two resulting gamma-ray flux limits are essentially identical, the two distributions being indistinguishable to the GRS. We discuss only the point source results here.

The 99% confidence limit of 1.2×10^{-4} photons cm^{-2} s^{-1} on a steady 1.275 MeV flux from the Galactic center direction is more than a factor of 3 below the only previous such measurement, by the *HEAO 3* gamma-ray spectrometer (Mahoney *et al.* 1982). Our flux limit, which assumes no other sources of emission, implies a limit of 3.1×10^{-6} $M_\odot$ on the mass of ^{22}Na in the vicinity of the Galactic nucleus (at a distance of 10 kpc). In terms of the frequency of ^{22}Na-producing novae in the Galactic bulge, R_N, the limit on the average mass of ^{22}Na ejected per nova is then

$$M_{\rm ej}(^{22}{\rm Na}) \leq 2.1 \times 10^{-8}\left(\frac{R_N}{40\ {\rm yr}^{-1}}\right)^{-1} M_\odot\ . \quad (1)$$

Similarly the average mass fraction of ^{22}Na in the novae ejecta, $X(^{22}{\rm Na})$, for total mass ejected per nova, $M_{\rm ej}$, is

$$X(^{22}{\rm Na}) \leq 2.1 \times 10^{-4}\left(\frac{R_N}{40\ {\rm yr}^{-1}}\right)^{-1}\left(\frac{M_{\rm ej}}{10^{-4}\ M_\odot}\right)^{-1}\ . \quad (2)$$

The frequency of 40 yr^{-1} is the canonical value and is roughly what one obtains when extrapolating the observed local Galactic frequency (i.e., disk novae) to the spheroidal frequency by comparison to the same quantities in M31. It is unclear how these quantities should be related to one another; thus this procedure is somewhat ambiguous. For example, Higdon and Fowler (1987) obtain a smaller value for the Galactic spheroidal component nova frequency by scaling that quantity for M31 by the ratio of bulge luminosities.

This limit can be compared to theoretical estimates of the production of ^{22}Na. To date, no published hydrodynamic models of novae include reaction networks which encompass all of the relevant mass range. However, several authors have performed parametric nova nucleosynthesis calculations which yield reliable results for the rearrangement of the nuclear species, at least for certain regions of the nova envelope (Wallace and Woosley 1981; Hillebrandt and Thielemann 1982; Wiescher *et al.* 1986; Hoffman and Woosley 1986). They follow in detail the nuclear reactions occurring along temperature and density paths which approximate those of published numerical hydrodynamic nova models. All of these authors, for all their various parameterizations of temperature and density, find the resulting mass fraction of ^{22}Na within a factor of 5 of $X(^{22}\mathrm{Na}) = 10^{-7}$, when the simulation begins with solar abundance of neon. Hoffman and Woosley (1986) find that the production of ^{22}Na scales linearly with the initial ^{20}Ne abundance, as might be expected. Clearly our gamma-ray limits can place no restrictions on even those models which are most productive of ^{22}Na [with $X(^{22}\mathrm{Na}) = 5 \times 10^{-7}$], even when applying the highest reasonable values of the nova frequency, ejected mass, and initial Ne abundances.

However, those nucleosynthesis calculations might misrepresent the production of some isotopes in an actual nova envelope where regions characterized by a wide range of temperatures are connected by rapid convection (see the discussion of Lazareff *et al.* 1979). Hoffman and Woosley (1986), in calculations otherwise identical to those mentioned above, but employing a technique simulating the effects of mixing, find that the production of ^{22}Na can be increased by orders of magnitude by this situation. In matter initially of solar composition, they find a final mass fraction of $X(^{22}\mathrm{Na}) = 7 \times 10^{-5}$. Our limit just allows for this production of ^{22}Na in 40 novae yr^{-1}, which on the average eject 10^{-4} $M_\odot$ from envelopes which start with 3 times the solar abundance of ^{20}Ne (assuming $X_\odot(\mathrm{Ne}) = 1.5 \times 10^{-3}$; Cameron 1982).

Neon-rich novae are expected to eject less total mass, $\sim 2 \times 10^{-5}$ $M_\odot$, and occur less often, comprising perhaps $\frac{1}{4}$ of all novae (Starrfield, Truran, and Sparks 1986). If 10 such novae occur in the inner Galaxy per year, the gamma-ray limit obtained here implies that, on the average, their preoutburst envelopes are enriched with neon by less than a factor of 60, if the burning produces $X(^{22}\mathrm{Na}) = 7 \times 10^{-5}$ per unit solar abundance of neon. Some observed novae have been interpreted as being ≥ 100 times overabundant in neon (see below), but the production of ^{22}Na or the frequency of these novae could easily be half of the values employed here.

Higdon and Fowler (1987) used the *HEAO 3* measurement to set a 90% confidence limit of 6×10^{-7} $M_\odot$ of ^{22}Na per neon-rich disk nova via statistical arguments. Basically, they found from a Monte Carlo simulation of the times and locations of nova outbursts that there ought to have been a few such novae within 2–3 kpc of the Sun in the last few ^{22}Na lifetimes (if the higher points of their Fig. 1 can be interpreted as arising from single novae). In fact, a few such novae have been discovered and they are discussed below. One can essentially scale the results of Higdon and Fowler (1987) downward by a factor of 3 to apply such statistical arguments with the *SMM* result to disk novae. Of course, we do not know in which galaxy of the statistical ensemble of galaxies we currently live.

A nuclear reaction sequence analogous to that which produces ^{22}Na could produce radioactive ^{26}Al from seed magnesium in the nova envelope. Aluminum 26 has been detected in the interstellar medium from its decay gamma rays (Mahoney *et al.* 1984; Share *et al.* 1985). If all of the observed ^{26}Al is from novae (but there are several other proposed sources; see Clayton and Leising 1987), the production ratio $X(^{22}\mathrm{Na})/X(^{26}\mathrm{Al}) \leq 0.3$, assuming the distributions of the two emissions are the same. Hoffman and Woosley (1986) found this ratio to be 0.6 for models with the prescription for mixing, but much lower in the single zone models, because ^{22}Na production is more sensitive to the effects of convection than is that of ^{26}Al.

Sodium 22 is also a possible source of the interstellar positrons whose annihilation photons have been observed. Because most of those positrons would annihilate via positronium decay, ^{22}Na can account for at most 6×10^{-5} 0.511 MeV photons cm^{-2} s^{-1}, or only about 4% of the annihilation line flux detected by the *SMM* GRS (Share *et al.* 1988).

b) Observed Neon-rich Novae

The comparison of a gamma-ray flux limit to that expected from an individual nova is somewhat more straightforward. However, interpretation of nova observations is not unambiguous; distance, ejected mass, and abundance determinations are uncertain. We proceed first under the assumption that each individual nova is the only source of 1.275 MeV emission, thus obtaining the most conservative limits on the mass of ^{22}Na ejected by each.

i) *Nova Cygni 1975 (V1500 Cygni)*

Nova Cygni 1975, the brightest nova in several decades, exceeded second magnitude in late 1975 August and was an extremely fast nova. It was observed to be overabundant in CNO elements and comparably enriched in neon (Ferland and Shields 1978*a*, *b*). The *SMM* GRS sensitivity to ejected ^{22}Na, reduced by the delay between outburst and observation, is further reduced by the nova's position, which transits the GRS field of view off-center. Our limit of 2.5×10^{-3} photons cm^{-2} s^{-1} at outburst is about 50% higher than that reported by Leventhal, MacCallum, and Watts (1977) from their 1976 balloon flight of a gamma-ray telescope. At a distance of 1.5 kpc (Gallagher and Ney 1976; Young *et al.* 1976) this flux corresponds to 1.5×10^{-6} $M_\odot$ of ^{22}Na. Ferland and Shields (1978*b*) found the neon abundance to be $X(\mathrm{Ne}) = 0.023$ (15 times solar) in the 10^{-4} $M_\odot$ ejecta. Our gamma-ray limit implies $X(^{22}\mathrm{Na})/X(\mathrm{Ne}) \leq 0.65$, which is not particularly interesting, as even for "convective" models Hoffman and Woosley (1986) calculate this ratio to be 0.07.

ii) *Nova Coronae Austrinae 1981*

Although the 1.275 MeV flux limit for this nova is comparable to those of the others, and it was observed to be greatly enriched in neon (Williams *et al.* 1985), the limit on the ^{22}Na mass produced is not especially informative because of the distance to the nova. It is however, the distance to this nova that makes it particularly interesting. It is probably located in the Galactic bulge (Brosch 1982), indicating that very neon-rich novae can also occur in that older population. If so, the limit on the ^{22}Na content of the Galactic center region is more significant, as discussed above. The flux limit quoted in Table 1 corresponds to a limit on the ejected mass of ^{22}Na of 8.6×10^{-6} $M_\odot$.

iii) *Nova Aquilae 1982*

The flux limit at 1.275 MeV at outburst, 2.5×10^{-4} photons cm^{-2} s^{-1}, implies an upper limit of 1.6×10^{-6} $M_\odot$ $(D/5\ \mathrm{kpc})^2$ of ^{22}Na produced. We note that some authors derive smaller values for the distance to this nova (e.g., 2.5 kpc, Williams and

Longmore 1984), but we adopt the distance estimate of Snijders *et al.* (1987) for this discussion. Even though this is a relatively well-observed nova, determinations of ejected mass and abundances therein are subject to interpretation. Like other neon-rich novae, Nova Aquilae had strong neon emission lines. Snijders *et al.* (1987) suggest, however, that neon is not enriched relative to C, O, Mg, or Si, but that those elements are depleted in the gas by grain formation. They find, however, that the ejecta is deficient in hydrogen. They describe three components of the gas, and their estimates indicate that the emission-line gas and grains contain perhaps 2.0×10^{-5} $M_\odot$. Averaged over the "medium-velocity gas" and grains, Snijders *et al.* (1987) find the mass fraction of neon to be $X(\mathrm{Ne}) = 0.15$. Thus the gamma-ray limit implies $X(^{22}\mathrm{Na})/X(\mathrm{Ne}) \leq 0.53$ in that matter, a limit which is not in conflict with the theory of the nuclear processing. If the "high-velocity gas," estimated to contain 10^{-3} $M_\odot$ to explain the radio emission (Snijders *et al.* 1987), participated in the nuclear processing, the implied ^{22}Na to neon ratio would be 50 times lower, constraining the convective nucleosynthesis models.

iv) *Nova Vulpeculae 1984 No. 2*

Nova Vulpeculae 1984 No. 2 was another nova with remarkably strong emission lines of neon (Gehrz, Grasdalen, and Hackwell 1985; Starrfield *et al.* 1986). Our limit of 3.0×10^{-4} photons cm^{-2} s^{-1} in the 1.275 MeV line at outburst corresponds to $M(^{22}\mathrm{Na}) \leq 7.0 \times 10^{-7}$ $(D/3\ \mathrm{kpc})^2$ $M_\odot$. The distance of 3.0 kpc was estimated by Gehrz, Grasdalen, and Hackwell (1985). If we assume that, like the two previously discussed novae, 2×10^{-5} $M_\odot$ were ejected with $X(\mathrm{Ne}) = 0.15$, the implied limit on the ^{22}Na mass fraction is $X(^{22}\mathrm{Na}) \leq 0.035$, and $X(^{22}\mathrm{Na})/X(\mathrm{Ne}) \leq 0.23$.

v) *Combined Emission from Four Novae*

The above limits were determined under the assumption that no other celestial sources of 1.275 MeV emission were present. Because all four above novae are at ecliptic longitudes within 70° of each other, the annual increases in the GRS counting rate due to each would occur at about the same time of year. We calculate another model of the expected variation of the measured intensity assuming that the same mass of ^{22}Na was produced in each outburst and that they are at the distances stated above. Varying the ^{22}Na mass from the value of the best fit to the data yields a 99% confidence limit of 4.6×10^{-7} $M_\odot$ of ^{22}Na ejected by each nova. This would limit the production of ^{22}Na to about 2% by mass. Because the time of year of the passage of the Galactic center through the GRS field of view nearly coincides with those of the four observed neon-rich novae, the expectation of one or more unobserved identical novae per year near the Galactic nucleus would further reduce the limit on the production of ^{22}Na by each.

IV. CONCLUSIONS

In the *SMM* GRS data we have found no excess of photons at 1.275 MeV above instrumental background. We have set rigorous limits on the mass of ^{22}Na from the Galactic center region and from individual novae which appear to be extremely rich in neon (see Table 1). None of these limits are in conflict with current thinking about the production of ^{22}Na in the explosive hydrogen burning of a nova. The most ^{22}Na that one could reasonably expect to be produced in a nova outburst is $\sim 10^{-6}$ $M_\odot$, taking the most efficient calculated production of ^{22}Na in 10^{-4} $M_\odot$ of processed and ejected matter which started with the highest abundance of neon observed in a nova. Our limits for individual novae are comparable to this, but it is likely, from both observational and theoretical considerations, that the total mass ejected from neon-rich novae is more nearly 10^{-5} $M_\odot$. The mass of neon ejected, the best quantity for prediction of the mass of ^{22}Na produced, is not easily observed.

Estimating the expected steady gamma-line flux from the collective ejecta of many novae of the inner Galactic spheroid is confounded by the uncertainty of what the actual frequency of novae is there. The *SMM* limit on the 1.275 MeV flux does constrain the rate of occurrence of very neon-rich novae in the bulge, but only if the higher estimates of ^{22}Na production are assumed, and even then not very severely. At the maximum calculated ^{22}Na production, $X(^{22}\mathrm{Na}) = 7 \times 10^{-5}$ per unit solar neon abundance, there can occur at most 6 novae yr^{-1} with average preoutburst enrichments of neon of 100, and which eject 2×10^{-5} $M_\odot$ of material.

If all of the ^{26}Al detected in the interstellar medium were ejected by novae, the production ratio of ^{22}Na to ^{26}Al in novae would be ≤ 0.3. Sodium 22 is not presently an important contributor of positrons to the Galaxy, accounting for, at most, a few percent of the observed 0.511 MeV gamma-ray flux.

As for the future, the Gamma-Ray Observatory, to be launched within the next few years, will contain the oriented scintillation spectrometer experiment and the imaging Compton telescope, Comptel, both of which can detect line photons at fluxes of 2×10^{-5} photons cm^{-2} s^{-1} (Kurfess *et al.* 1983; Schönfelder *et al.* 1984). This flux corresponds to a ^{22}Na mass of 5×10^{-9} $(D/1\ \mathrm{kpc})^2$ $M_\odot$ at distance D. The occurrence of a neon-rich nova within a couple of kiloparsecs during that mission would offer the best hope of detecting ^{22}Na in a nova or of constraining theories of its production.

We wish to thank Bob Kinzer, Bill Purcell, Dan Messina, and Steve Matz for software development and production data analysis related to this project. We are indebted to Dave Forrest, Claus Reppin, and Erich Rieger for their efforts in the development of the instrument and in understanding its operational characteristics. We thank Jim Kurfess for a careful reading of the manuscript. This work was done while Mark Leising held a National Research Council–Naval Research Laboratory Research Associateship and was supported by NASA contract S-14513-D at the Naval Research Laboratory and grant NAS 5-28609 at the University of New Hampshire, and by BMFT contract 010k 017-za/ws/wrk 0275:4 at the Max Planck Institute.

REFERENCES

Brosch, N. 1982, *Astr. Ap.*, **107**, 300.
Cameron, A. G. W. 1982, in *Essays in Nuclear Astrophysics*, ed. C. A. Barnes, D. D. Clayton, and D. N. Schramm (Cambridge: Cambridge University Press), p. 23.
Ciardullo, R., Ford, H. C., Neill, J. D., Jacoby, G. H., and Shafter, A. W. 1987, *Ap. J.*, **318**, 520.
Clayton, D. D., and Hoyle, F. 1974, *Ap. J.* (*Letters*), **187**, L101.
Clayton, D. D., and Leising, M. D. 1987, *Phys. Rept.*, **144**, 1.
Ferland, G. J., and Shields, G. A. 1978*a*, *Ap. J.* (*Letters*), **224**, L15.
———. 1978*b*, *Ap. J.*, **226**, 172.
Forrest, D. J., *et al.* 1980, *Solar Phys.*, **65**, 15.
Gallagher, J. S., and Ney, E. P. 1976, *Ap. J.* (*Letters*), **204**, L35.
Gallagher, J. S., and Starrfield, S. 1978, *Ann. Rev. Astr. Ap.*, **16**, 171.
Gehrz, R. D., Grasdalen, G. L., and Hackwell, J. A. 1985, *Ap. J.* (*Letters*), **298**, L47.
Higdon, J. C., and Fowler, W. A. 1987, *Ap. J.*, **317**, 710.

Hillebrandt, W., and Thielemann, F.-K. 1982, *Ap. J.*, **255**, 617.
Hoffman, R. D., and Woosley, S. E. 1986, *Bull. AAS*, Vol. **18**, No. 4, p. 948.
Kopylov, I. M. 1955, *Izv. Krymsk. Astrofiz. Obs.*, **13**, 23.
Kurfess, J. D., Johnson, W. N., Kinzer, R. L., Share, G. H., Strickman, M. S., Ulmer, M. P., Clayton, D. D., and Dyer, C. S. 1983, *Adv. Space Res.*, **3**, 109.
Lampton, M., Margon, B., and Bowyer, S. 1976, *Ap. J.*, **208**, 177.
Lazareff, B., Audouze, J., Starrfield, S., and Truran, J. W. 1979, *Ap. J.*, **228**, 875.
Leising, M. D., and Clayton, D. D. 1985, *Ap. J.*, **294**, 591.
Leventhal, M., MacCallum, C., and Watts, A. 1977, *Ap. J.*, **216**, 491.
Mahoney, W. A., Ling, J. C., Jacobson, A. S., and Lingenfelter, R. E. 1982, *Ap. J.*, **262**, 742.
Mahoney, W. A., Ling, J. C., Wheaton, W. A., and Jacobson, A. S. 1984, *Ap. J.*, **286**, 578.
Matz, S., and Jung, G. 1987, private communication.
Patterson, J. 1984, *Ap. J. Suppl.*, **54**, 443.
Schönfelder, V. *et al.* 1984, *IEEE Trans. Nucl. Sci.*, **31**, 766.
Share, G. H., Kinzer, R. L., Kurfess, J. D., Forrest, D. J., Chupp, E. L., and Rieger, E. 1985, *Ap. J. (Letters)*, **292**, L61.
Share, G. H., Kinzer, R. L., Kurfess, J. D., Messina, D. C., Purcell, W. R., Chupp, E. L., Forrest, D. J., and Reppin, C. 1988, *Ap. J.*, **326**, in press.
Sharov, A. S. 1971, *Astr. Zh.*, **48**, 1258.
Snijders, M. A. J., Batt, T. J., Roche, P. F., Seaton, M. J., Morton, D. C., Spoelstra, T. A. T., and Blades, J. C. 1987, *M.N.R.A.S.*, in press.
Starrfield, S., Sparks, W. M., and Truran, J. W. 1974, *Ap. J. Suppl.*, **28**, 247.
Starrfield, S., Truran, J. W., and Sparks, W. M. 1978, *Ap. J.*, **226**, 186.
———. 1986, *Ap. J. (Letters)*, **303**, L5.
Truran, J. W. 1982, in *Essays in Nuclear Astrophysics*, ed. C. A. Barnes, D. D. Clayton, and D. N. Schramm (Cambridge: Cambridge University Press), p. 467.
Wallace, R. K., and Woosley, S. E. 1981, *Ap. J. Suppl.*, **45**, 389.
Wiescher, M., Görres, J., Thielemann, F.-K., and Ritter, H. 1986, *Astr. Ap.*, **160**, 56.
Williams, P. M., and Longmore, A. J. 1984, *M.N.R.A.S.*, **207**, 139.
Williams, R. E., Ney, E. P., Sparks, W. M., Starrfield, S. G., Wyckoff, S., and Truran, J. W. 1985, *M.N.R.A.S.*, **212**, 753.
Young, P. J., Corwin, H. G., Jr., Bryan, J., and de Vaucouleurs, G. 1976, *Ap. J.*, **209**, 882.

EDWARD L. CHUPP: Physics Department, University of New Hampshire, Durham, New Hampshire 03824

GOTTFRIED KANBACH: Max-Planck-Institut für Physik und Astrophysik, Institut für Extraterrestrische Physik, 8046 Garching bei München, FRG

MARK D. LEISING and GERALD H. SHARE: Mail Code 4152, Naval Research Laboratory, Washington, D.C. 20375-5000