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Michael J. Harris
*Naval Research Lab*

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

Gerald H. Share
*Naval Research Lab*

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# A SEARCH FOR THE 478 keV LINE FROM THE DECAY OF NUCLEOSYNTHETIC $^7$Be

MICHAEL J. HARRIS
S M Systems and Research Corporation, Suite 510, 8401 Corporate Drive, Landover, MD 20785
AND
MARK D. LEISING AND GERALD H. SHARE
E. O. Hulburt Center for Space Research, Mail Code 4150, Naval Research Laboratory, Washington, DC 20375-5000
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## ABSTRACT

Unstable $^7$Be (half-life 53.28 days) is expected to be present in the ejecta of classical novae. If the frequency of novae in the central Galaxy is high enough, a nearly steady state abundance of $^7$Be will be present there. Data accumulated during transits of the Galactic center across the aperture of the *Solar Maximum Mission* Gamma Ray Spectrometer have been searched for evidence of the 478 keV $\gamma$-ray line resulting from $^7$Be decay. A 3 $\sigma$ upper limit of $1.6 \times 10^{-4}$ $\gamma$ (cm$^2$ s)$^{-1}$ has been placed on the emission in this line from the central radian of the Galactic plane. Less stringent limits have been set on the production of $^7$Be in Nova Aquilae 1982, Nova Vulpeculae 1984 No. 2, and Nova Centauri 1986 from observations with the same instrument.

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

## 1. INTRODUCTION

The abundance of $^7$Li produced by standard big bang models, a mass fraction of $\sim 10^{-9}$, is compatible with that observed in Population II dwarf stars (Kawano, Schramm, & Steigman 1988). However, some nonstandard models ($\Omega_B = 1$), incorporating a quark-hadron phase transition prior to nucleosynthesis, predict a mass fraction of $\sim 10^{-8}$, which is closer to that observed in Population I material (Applegate, Hogan, & Scherrer 1987). The standard models require that the primordial $^7$Li abundance must be enhanced by subsequent stellar nucleosynthesis, while the $\Omega_B = 1$ models require primordial $^7$Li to be destroyed by some mechanism in Population II dwarfs. This problem would be clarified if a stellar source of $^7$Li were identifiable.

Several possibilities have been suggested for the stellar source of $^7$Li. In all of them $^3$He, formed by low-temperature hydrogen burning, undergoes the reaction $^3$He($\alpha$, $\gamma$)$^7$Be followed by $\beta$-decay of the $^7$Be. Starrfield et al. (1978) suggested nova explosions as a promising site for this process. If this is the case, Clayton (1981) pointed out that then the 478 keV line from the $\beta$-decay (branching ratio 0.104) might be observable from a nearby nova. Leising (1988) further suggested that the Galactic center (GC) region might be a source of this radiation since, despite the short (53.28 days) half-life, the frequency of novae ($\sim 40$ yr$^{-1}$) in that direction is high enough for a significant steady state abundance of $^7$Be to be present.

In this paper the results from the first search for this line are reported. Analysis of the Gamma Ray Spectrometer (GRS) data from the *Solar Maximum Mission* (*SMM*) has set upper limits on the 478 keV line flux from the GC region and from three individual novae in the Galactic disk (Nova Aquilae 1982, Nova Vulpeculae 1984 No. 2, and Nova Centauri 1986). These results are described in § 2. In § 3 the relevance of these limits to the nucleosynthesis of $^7$Li in novae is discussed. Since the source of the $^7$Be is $^3$He, limits on the synthesis of that isotope in red giants have also been derived in § 3.

## 2. ANALYSIS AND RESULTS

### 2.1. *The Galactic Center Region as a Source*

Our method of analysis closely follows that used by Leising et al. (1988) to set limits on the 1.275 MeV line from $\beta$-decay of $^{22}$Na in the GC and in individual novae. It exploits the fact that the GRS was pointed at the Sun during the lifetime of *SMM* (1980 February to 1989 December), during which time it accumulated data continuously except for a 5 month hiatus (1983 November to 1984 April). As a result the GC region transited the GRS aperture every year; the GRS aperture was so broad ($\sim 130°$ FWHM at 511 keV) that the transits, centered on the Sun's crossing of the Galactic equator in December, lasted for several months. Enhanced count rates were measured by the GRS during these transits in $\gamma$-ray lines at 0.511 and 1.809 MeV (Share et al. 1985, 1988) and in the continuum between 0.3 and 8.5 MeV (Harris et al. 1990). These emissions are attributed to an extended source along the Galactic plane.

Our method of analysis involves searching for comparable increased count rates in a line at 478 keV. Data taken between 1980 February and 1989 March were summed to 1 minute accumulations in 476 energy channels between 0.3 and 8.5 MeV. After rejecting data coinciding with solar flares, $\gamma$-ray bursts, and transient backgrounds, these spectra were further summed over 3 day intervals. Data accumulated in orbits traversing the South Atlantic Anomaly, or less than $10^4$ s after a crossing, were rejected, since these spectra are dominated by short-lived radioactive features produced by proton bombardment. The 3 day spectra were summed into two categories, "Earth-viewing" with $108° \leq \theta \leq 252°$ and "sky-viewing" with $288° \leq \theta \leq 360°$, $0° < \theta \leq 72°$ where $\theta$ is the angle formed by the Sun, the center of the Earth, and *SMM*.

The major backgrounds in the resulting 3 day "Earth-view" and "sky-view" spectra were prompt cosmic-ray events, the albedo emission from Earth's atmosphere, and emissions from long-lived radioactivities in the detector and spacecraft.

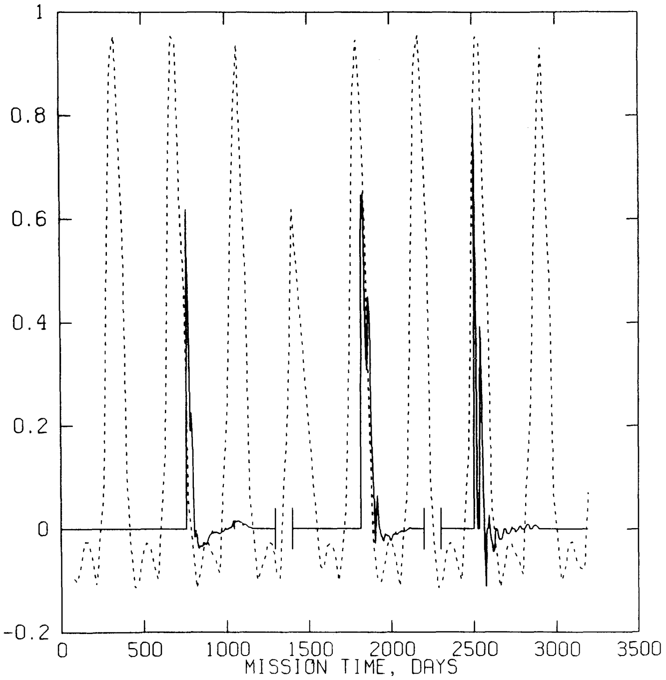

FIG. 1.—Exposure of the GRS aperture at 511 keV to three individual novae (N Aql 1982, N Vul 1984 No. 2, and N Cen 1986—*full lines*), and to a point source at the Galactic center (*dashed line*). The abscissa is expressed in days after 1980 January 0.

However, the intensities of the radioactive features varied sufficiently slowly that they were eliminated when the "sky-view" spectrum was subtracted from the "Earth-view" spectrum. The resulting 3 day "Earth minus sky-view" spectrum was basically that of the Earth's atmosphere, with a much weaker spectrum from the celestial ("sky") source superposed "in negative." Residual radioactive features have been found to be very weak in such a spectrum. The Earth-albedo spectrum in the energy range of interest is dominated by the 511 keV line due to positron annihilation in the atmosphere, together with a continuum below 511 keV due to Compton scattering of these line photons, plus a power law at energies above 511 keV (Harris et al. 1990).

The spectrum of the GC was separated from that of Earth's atmosphere by means of its distinctive annually transiting time signature. The expected exposure of the GRS to the GC was computed from Monte Carlo estimates of its angular response at 0.511 MeV (S. M. Matz & G. V. Jung 1988, private communication) for three different assumed steady Galactic source distributions: a point source at the GC (*dashed line* in Fig. 1); a distribution derived for a spheroidal concentration of novae by Leising & Clayton (1985); and a distribution derived by the same authors which followed radio measurements of CO emission, in other words a Population I tracer. After convolution with the GRS aperture, the exposures to the two extended distributions do not differ materially from the point source exposure (*dashed line* in Fig. 1). The time signature expected from atmospheric emission was taken to be that exhibited by a line visible in the spectra at 4.4 MeV, which is excited by proton impacts on atmospheric $^{14}N$ and $^{12}C$; this line does not appear to contain a significant contribution from a Galactic source (Share et al. 1991). The "Earth minus sky-view" spectra for each 3 day period were fitted between 300 and 800 keV by a four-component model containing a line from $e^-e^+$ annihilation at 511 keV, a Compton scattering continuum at energies below 511 keV, an underlying power law, and the $^7$Be decay line at 478 keV (an example is shown in Fig. 2). The Compton continuum was assumed to arise from scattering of the 511 keV line photons by ~26 g cm$^{-2}$ of N in

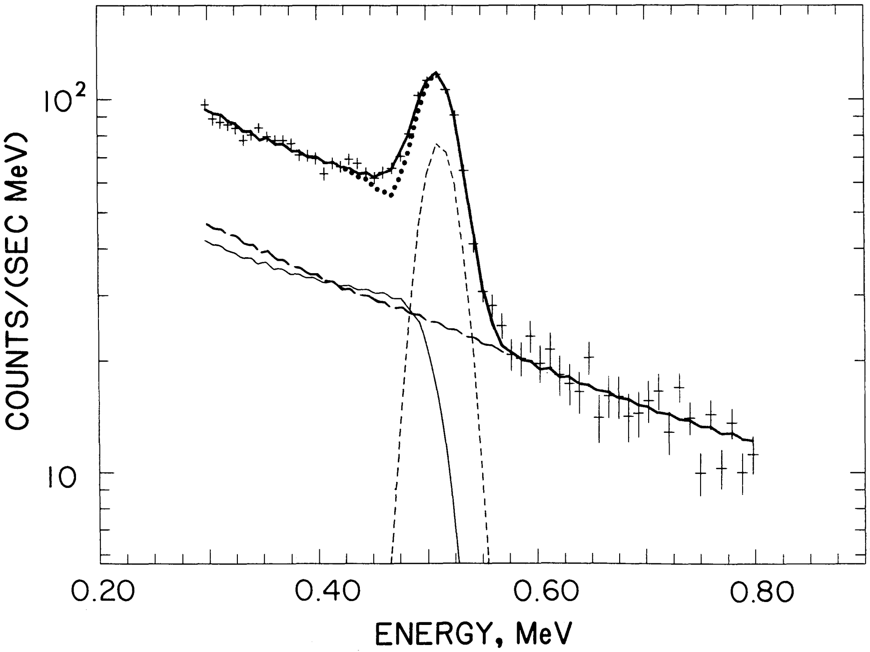

FIG. 2.—"Earth minus sky-view" count spectrum accumulated over the 3 day interval 1987 January 5–8. A four-component model (*see text*) fitted to it after propagation through the instrument response function is also shown. Bold line represents the best-fit model; three of the four components are also shown (*full line*—Compton scattering continuum; *short dashes*—511 keV annihilation line; *long dashes*—power law). Although no 478 keV line is required in this fit, the dotted line shows the effect of a Galactic line at 478 keV of intensity $2.5 \times 10^{-3}$ $\gamma$ (cm$^2$ s)$^{-1}$ added to the model.

Earth's atmosphere (full line in Fig. 2). The four-component model spectrum was folded with the GRS instrument response and compared with the 3 day count spectra to derive the strength of each of the four components during each 3 day period. This was accomplished by varying the strengths of the components to minimize the discrepancy between model and observation by the least-squares method (weighted according to the error in each channel of the spectrum). Errors in the strength of each component were estimated from the covariance matrix of the fit, that is, the matrix of the second derivatives of the $\chi^2$ parameter with respect to the strengths (Press et al. 1986). This procedure gives a realistic estimate of the error in the case of weak components such as the 478 keV line strength, upon which $\chi^2$ depends only weakly.

The time series of each of the components was then fitted to the GC transiting time series of Figure 1 plus the time series of 4.4 MeV line strengths from Earth's atmosphere (cf. Fig. 2 of Harris et al. 1990), by the same nonlinear least-squares method, taking into account the error on each 3 day time point obtained as described above. The best-fit amplitude for the transiting time series was taken to be the intensity of the corresponding component in the GC emission. The uncertainty in this amplitude was derived by the same method of varying $\chi^2$. Note that use of the GC transits as in Figure 1 is appropriate for a constant level of emission from the GC over the 9 yr period. Note also that we have neglected the Doppler broadening and shifting of the 478 keV line due to the velocity of the nova ejecta. Most of the material containing $^7$Be will be optically thin to this line, so that both blue- and redshifted material will contribute, in which case a broadening, but no net shift, is expected. However, for characteristic nova velocities $\sim 2000$ km s$^{-1}$ the broadening is very small compared to the GRS instrumental broadening.

### 2.2. *Three Individual Disk Novae*

Exposures of the GRS to point sources at the positions of N Aql 1982, N Vul 1984 No. 2, and N Cen 1986 were calculated in the same way as the transiting GC exposures described in the previous section. However, the time signatures of transient sources will differ in obvious ways from the regular transits of a quasi-steady source such as the GC. Clearly no emission would be expected before the epoch of the nova outburst, and the exposure was set to zero for these times. It was assumed that any $^7$Be was produced instantaneously, so that the exposure thereafter would be expected to decay exponentially with a 53.28 day half-life. For fast novae the nucleosynthesis was assumed to occur at the epoch of maximum *V* brightness (e.g., N Vul 1984 No. 2; N Aql 1982 was assumed to be at maximum at the time of discovery, since its rise to maximum was not observed). For slow novae such as N Cen 1986 the model of Sparks, Starrfield, & Truran (1978) suggests that the start of the rise from minimum light is a better approximation to the epoch of nucleosynthesis (however, it is not clear that slow novae produce any $^7$Be at all—see model 7 of Starrfield et al. 1978).

The resulting exposures to these three novae are shown as the full lines in Figure 1.[1]

The time series of intensities of the 478 keV line, obtained as described above, was fitted to each nova exposure time series plus the Earth's atmosphere time series in just the same way as was described for the GC source.

### 2.3. *Results*

The time series of intensities of the 511 keV line, the Compton continuum, and the power law fitted to the spectra as in Figure 2 showed clear evidence of variations following the transits of the GC. The amplitudes of these transits were in good agreement with those found for the same spectral components by Harris et al. (1990) from the variation of the counts

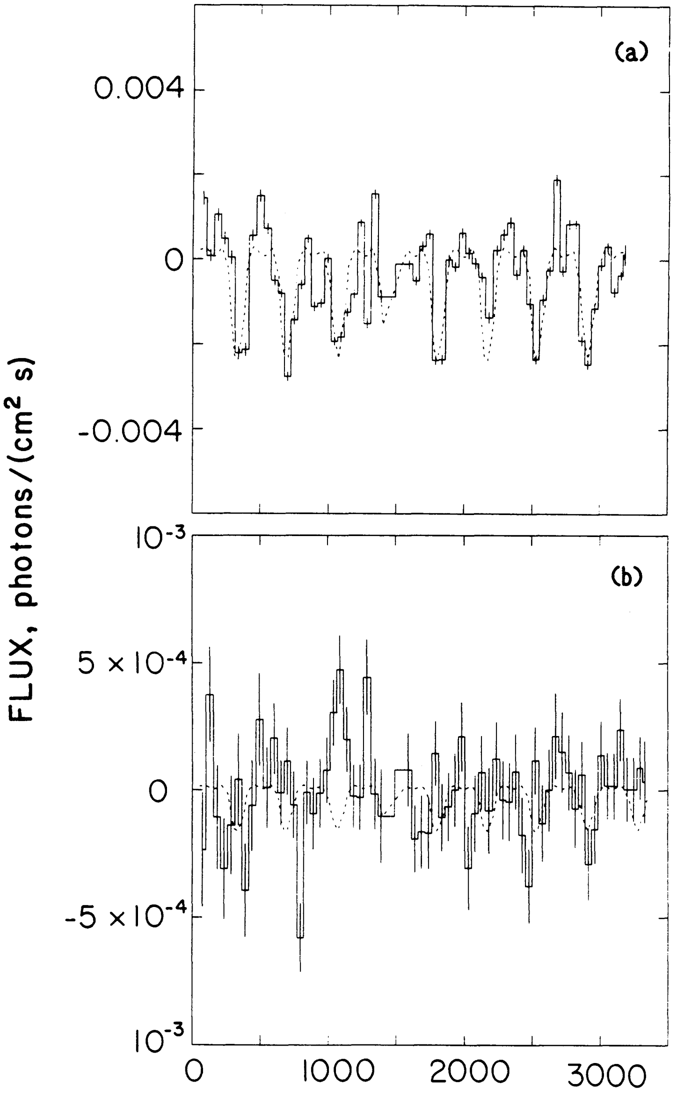

FIG. 3.—(*a*) Intensities of the 511 keV line from fits to the 3 day "Earth minus sky-view" spectra (see Fig. 2) throughout the mission. The fitted background varying as the 4.4 MeV line has been subtracted (*see text*), and the intensities have been summed to 48 days for illustrative purposes. Error bars are 1 $\sigma$. Dashed line represents the variation expected from a point source at the GC with intensity $2.3 \times 10^{-3}$ $\gamma$ (cm$^2$ s)$^{-1}$. The abscissa is expressed in days after 1980 January 0. (*b*) Intensities of the 478 keV line obtained in the same fashion. Dashed line represents the variation expected from a point source at the GC at a constant level of $1.7 \times 10^{-4}$ $\gamma$ (cm$^2$ s)$^{-1}$ (our 3 $\sigma$ upper limit; see Table 1).

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[1] If a point source were situated sufficiently far from the plane of *SMM*'s orbit, Earth failed to occult it during the GRS's Earthward-looking exposures. The exposure of the "Earth minus sky-viewing" data set fell to zero during these times (cf. the situation described by Leising & Share 1990 for SN 1987A). The sharp drops in the full-line exposures in Fig. 1 are due to this effect, which recurred with a period of 48 days because of the precession of *SMM*'s orbital plane.

in each channel of the GRS (the transiting part of the "Compton" continuum reflects the contribution from the continuum due to annihilation in the Galaxy of positrons via positronium formation into three photons, as discussed by Harris et al.). The intensities of the fitted 511 keV lines are shown in Figure 3*a*. They exhibit clear evidence of annual transits of amplitude $2.5 \pm 0.2 \times 10^{-3}$ $\gamma$ (cm$^2$ s)$^{-1}$ (1 $\sigma$ statistical error only). This result is in good agreement with the values obtained for this line by Share et al. (1988) of $2.1 \pm 0.4 \times 10^{-3}$ $\gamma$ (cm$^2$ s)$^{-1}$ and by Harris et al. (1990) of 2.7 ($-0.7$, $+0.6$) $\times 10^{-3}$ $\gamma$ (cm$^2$ s)$^{-1}$.

In contrast, the amplitudes of a line fitted at 478 keV showed no such transiting behavior (Fig. 3*b*). Only an upper limit could therefore be derived for the Galactic intensity of this line. This limit was essentially independent of our choice of model of source distribution. Our result for a point source at the GC is given in Table 1 (col. [3]).[2]

No significant increases were found in the amplitudes of the 478 keV line due to *SMM*'s exposure to any of the three individual novae (cf. Fig. 1 [*full lines*] and Fig. 3*b*). The results and 3 $\sigma$ uncertainties obtained for the fluxes at the time of outburst are given in columns (3) and (4) of Table 1. The value for N Cen 1986 is dependent on our assumption that the epoch of nucleosynthesis is the time of first rise from minimum light (which for this nova was 1986 November 8). If the synthesis of $^7$Be occurred instead around the time of maximum *V* brightness (1986 November 24), our result for the flux becomes $1.4 \pm 5.6 \times 10^{-4}$ $\gamma$ (cm$^2$ s)$^{-1}$.

## 3. DISCUSSION

### 3.1. *Nucleosynthesis of* $^7$Li *in Novae*

The upper limits on the mass of $^7$Be allowed by our limits on the 478 keV line flux depend on the distances assumed for each source; these are given in Table 1 (col. [2]). For the three disk novae the limits are a few times $10^{-7}$ $M_\odot$ of $^7$Be per event. The GC region is expected to contain, at any time, the $^7$Be from a number of novae $\sim R_N\, \tau(^7\mathrm{Be}) \sim 8$, where $R_N \sim 40$ yr$^{-1}$ (Allen 1973) is the expected rate at which novae occur in the Galactic bulge. Virtually all such novae must have lain within the GC region as seen by the broad GRS field of view. Hence the limit of $5.5 \times 10^{-7}$ $M_\odot$ present in the GC region implies an upper limit of $6.4 \times 10^{-8}$ $M_\odot$ on the average yield of $^7$Be from each nova in that region.

The yield of $^7$Be expected from the thermonuclear runaway model of novae is highly uncertain. Several models of fast novae by Starrfield et al. (1978) produced an average of $\sim 2.5 \times 10^{-10}$ $M_\odot$ of $^7$Be per nova (under the assumption that a total of $\sim 10^{-4}$ $M_\odot$ escapes from a typical nova). However, this value was obtained from an initial $^3$He abundance $X(^3\mathrm{He})$ which was approximately solar. In the model the ultimate source of the material experiencing the thermonuclear runaway is the envelope of a low-mass red giant, which undergoes accretion onto a white dwarf. Models of red giant star evolution suggest that $X(^3\mathrm{He})$ is enhanced by 2–20 times over the Starrfield et al. value (see next section). If the yield of $^7$Be is proportional to $X(^3\mathrm{He})$, as expected, then the average fast nova event may yield up to $5 \times 10^{-9}$ $M_\odot$ of $^7$Be. This is comparable to the value $\sim 4 \times 10^{-9}$ $M_\odot$ per nova required for the synthesis of the solar $^7$Li abundance over Galactic history at the observed nova rate.

The $^7$Be abundance in the GC direction, being averaged over $\sim 8$ novae at any one time, would be expected to reflect this average nova yield. In this case our upper limit $6.4 \times 10^{-8}$ $M_\odot$ is about an order of magnitude above theoretical expectations. However, Clayton (1981) cautioned that the yield from individual novae may vary from the average by a factor of 5 or so in either direction. Any individual nova may then produce a few times $10^{-8}$ $M_\odot$ of $^7$Be, which is again an order of magnitude below our limits on the abundances in the fast novae N Aql 1982 and N Vul 1984 No. 2.

In contrast to fast novae, in which rapid convection removes $^7$Be from the high-temperature regions, whereupon both convection and nucleosynthesis cease before its return (Leising & Clayton 1987), slow nova envelopes remain convective for a long period. This situation is unfavorable for the production of $^7$Be, which is destroyed by continual cycling through the high temperatures at the base of the convective region. It appears that $^7$Be production in the slow nova N Cen 1986 would be expected to be negligible, unless either the standard model of slow nova thermonuclear runaways is misleading, or else this nova has been misclassified.

### 3.2. *Nucleosynthesis of* $^3$He *in Red Giants*

The stellar models of Rood, Steigman, & Tinsley (1976) and Iben & Truran (1978) indicate that the $^3$He mass fraction in the

TABLE 1

478 keV LINE FLUXES AND $^7$Be ABUNDANCES

| Source (1) | Distance[a] (kpc) (2) | 478 keV Line Flux[b] ($\gamma$ (cm$^2$ s)$^{-1}$) (3) | Flux Upper Limit[c] (4) | $^7$Be Abundance[c] ($M_\odot$) (5) |
|---|---|---|---|---|
| GC[d] ........................ | 8.5 | $-1.5 \pm 5.1 \times 10^{-5}$ | $1.7 \times 10^{-4}$ | $\leq 5.0 \times 10^{-7}$ |
| N Aql 1982[e] ................ | 3.5 | $9 \pm 4 \times 10^{-4}$ | $2.0 \times 10^{-3}$ | $\leq 6.3 \times 10^{-7}$ |
| N Vul 1984 No. 2[e] ......... | 3.0 | $0.5 \pm 2.5 \times 10^{-4}$ | $8.1 \times 10^{-4}$ | $\leq 3.1 \times 10^{-7}$ |
| N Cen 1986[e] ................ | 1.1 | $-1.0 \pm 3.2 \times 10^{-4}$ | $1.1 \times 10^{-3}$ | $\leq 5.2 \times 10^{-8}$ |

[a] Distances from Williams & Longmore 1984 and Snijders et al. 1987 for N Aql 1982; Gehrz, Grasdalen, & Hackwell 1985 for N Vul 1984 No. 2; Schaefer 1988 for N Cen 1986.

[b] Uncertainties represent 67% confidence limits.

[c] Upper limits of 3 $\sigma$, obtained by adding the systematic error (absolute value of the measurement) to 3 times the 1 $\sigma$ error.

[d] Point source of constant intensity at Galactic center assumed.

[e] Fluxes and abundances are at time of outburst.

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[2] The value of $\chi^2$ per degree of freedom for the fit of the transiting time series is 1.15, if the 4.4 MeV time series is included in the fit in order to extract the variation of the atmospheric background, as described in § 2.1. If this 4.4 MeV time series is not included, an intensity of $8.8 \pm 5.0 \times 10^{-5}$ photons (cm$^2$ s)$^{-1}$ is found for the transits of the 478 keV line with a $\chi^2$ per degree of freedom of 1.63.

envelopes of low-mass red giants is $X(^3\mathrm{He}) \sim (0.5\text{–}2) \times 10^{-3}$. This abundance is greater for less massive stars, and roughly the same for Population I and Population II compositions. For comparison, an upper limit on $X(^3\mathrm{He})$ in those red giants which are involved in nova outbursts can be derived from our limits on the $^7$Be abundance if it is assumed that the fraction of the mass of $^3$He processed into $^7$Be is approximately the same in all novae. The fast nova models of Starrfield et al. (1978) suggest that this fraction is $\sim 0.05$, varying in different models by about a factor of 2.5 in each direction. Our limit of $6.4 \times 10^{-8}\ M_\odot$ of $^7$Be yielded by each nova in the GC direction then implies $X(^3\mathrm{He}) < 0.013$ if the novae each eject $\sim 10^{-4}\ M_\odot$ of material. Similarly our limit of a few times $10^{-7}\ M_\odot$ to $10^{-6}\ M_\odot$ of $^7$Be in the fast novae N Aql 1982 and N Vul 1984 No. 2 implies $X(^3\mathrm{He}) < 0.1$ for these objects. These values are each about an order of magnitude above the most optimistic theoretical expectations.

### 3.3. *Conclusions*

Our upper limits on the fluxes observed in the 478 keV line from both the GC region and from three disk novae imply limits on the $^7$Be abundance (and the $^3$He abundance in the red giant progenitors) in each which are about an order of magnitude above theoretical expectations. It is clear that instruments capable of detecting fluxes as low as a few times $10^{-5}\ \gamma\ (\mathrm{cm}^2\ \mathrm{s})^{-1}$ will be needed in order to put significant constraints on the theories, unless a very nearby nova ($< 1$ kpc) erupts. In the absence of such good fortune, even the Oriented Scintillation Spectrometer Experiment (OSSE) on board the *Gamma Ray Observatory*, with its point source sensitivity of $\sim 3 \times 10^{-5}\ \gamma\ (\mathrm{cm}^2\ \mathrm{s})^{-1}$ at 478 keV will be only marginally capable of detecting the 478 keV line from more distant novae. The likelihood of OSSE detecting the emission in this line from the GC region is even less, since its small aperture (4° × 11°) will include fewer novae in this direction than *SMM* did.

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