TRANSIENT GAMMA RAY SPECTROMETER OBSERVATIONS OF GAMMA-RAY LINES FROM NOVAE.
I. LIMITS ON THEPOSITRON ANNIHILATION LINE IN FIVE INDIVIDUAL NOVAE

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ABSTRACT

The Transient Gamma Ray Spectrometer (TGRS) on board the Wind spacecraft has spent most of the interval 1995–1997 in a high-altitude orbit where γ-ray backgrounds are low. Its high-resolution Ge spectrometer is thus able to detect weak lines that are slightly offset from stronger background features. One such line is predicted from nucleosynthesis in classical novae, where β decays on a timescale of a few hours in an expanding envelope produce positrons that annihilate to generate a line that is blue-shifted by a few keV away from the background annihilation line at 511 keV. The broad TGRS field of view contained five known Galactic novae during 1995 January–1997 June, and we have searched the spectra taken around the times of these events for the blueshifted nova annihilation line. Although no definite detections were made, the method is shown to be sensitive enough to detect novae occurring on ONeMg-rich white dwarfs out to about 2.5 kpc.

Subject headings: gamma rays: observations — novae, cataclysmic variables — nuclear reactions, nucleosynthesis, abundances — white dwarfs

1. INTRODUCTION

In the standard thermonuclear runaway model of classical nova outbursts, the energy source is the explosive burning of H in a degenerate layer on the surface of a white dwarf, composed of H-rich material accreted from a companion contaminated by material taken up from the white dwarf by diffusion. The nuclear burning timescale is rapid compared to the lifetimes of certain key β-unstable nuclei involved are all proton-rich and therefore decay predominantly by emission of positrons. Thus in addition to γ-rays from de-excitation of the daughter nuclei, we also expect a line at 511 keV from the annihilation of the positrons with the ambient material (Clayton & Hoyle 1974; Leising & Clayton 1987). Several previous experiments have searched for the decay lines from the relatively long-lived isotopes 22Na and 7Be, either from individual nearby novae (Leising et al. 1988; Iyudin et al. 1995) or from the accumulated production of many novae in a wide field of view (Leising et al. 1988; Harris, Leising, & Share 1991; Harris et al. 1997). Here we report results of the first search for the 511 keV line, which reflects primarily the production of shorter lived isotopes such as 13N and 14F.

The Transient Gamma Ray Spectrometer experiment (TGRS) is very well suited to the search for the 511 keV line for several reasons. First, it is located on board a spacecraft whose orbit is so elliptical that it has spent virtually all of its mission (1994 November–present) in interplanetary space (the Wind mission). In this environment the γ-ray background level is relatively low, and interruptions owing to passages of Earth’s trapped radiation belts are minimal (typically lasting a few hours at intervals of several months). This is important because the bursts of 511 keV radiation are predicted to occur only during a ~6 hr period at an uncertain interval before the nova event (Leising & Clayton 1987; Hernanz et al. 1997; see also § 2). Second, the TGRS instrument is attached to the south-facing surface of the rotating cylindrical Wind body, which points permanently toward the south ecliptic pole. The detector is unshielded, and TGRS therefore has an unobstructed view of the entire southern (ecliptic) hemisphere. Third, and most importantly, the TGRS Ge detector has sufficient spectral resolution to detect a 511 keV line that is slightly Doppler-shifted away from the background 511 keV line that is always present in space experiments, which arises from annihilation following β+ decays of cosmic-ray spallation product nuclei. This background line is always very close to the rest energy, whereas the most recent nova models predict the source line to be blueshifted by 2–5 keV (M. Hernanz 1997, private communication); by comparison, the TGRS energy resolution at 511 keV has varied from 3 to 4 keV FWHM during the mission (Harris et al. 1998). No previous experiment has possessed the same advantages of long and continuous temporal coverage, broad spatial coverage, and fine spectral resolution.

Our analysis procedure (described in § 3) relies heavily on the theoretically predicted properties of the 511 keV line. There has been no much incentive for theoretical work on this line because of the difficulty of resolving the nova line from the background line in the previous generation of low-resolution experiments. The early work of Clayton & Hoyle (1974) and Leising & Clayton (1987) assumed white dwarf models that were CO-rich and treated the explosion parametrically. Much fuller hydrodynamic models that can be applied at all stages from accretion through explosion and nucleosynthesis have recently been developed (Starrfield et al. 1992; Hernanz et al. 1996; José, Hernanz, & Coc 1997).

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and applied to the positron annihilation problem (Hernanz et al. 1997; Gómez-Gomar et al. 1998). In this series of models, the largest 511 keV line fluxes come from the more massive ONeMg-rich white dwarfs; indeed, fluxes as high as $10^{-2}$ photons cm$^{-2}$ s$^{-1}$ are expected in favorable cases. For the purpose of analysis we shall, in general, assume the line properties of the Hernanz et al. (1997) ONe2 model, which generates this level of flux over a $\sim 6$ hr period ($\S$ 3). In § 2 we describe the difficulties that are involved in a search for the 511 keV line around the times of those novae that are known to have been in TGRS’s field of view during the mission. Our results for the individual novae are presented in § 4, and we will show in § 5 that for the ONe2 and other nova models, TGRS sensitivity is good enough to justify a large-scale search for the line in the full 1995–1997 TGRS data.

2. SAMPLE OF NOVAE

There were five known classical novae in the southern hemisphere between 1995 January and 1997 June, the relevant properties of which are given in Table 1. It should be noted that in many cases the observational material on which they are based is extremely incomplete and their properties are often very poorly known. Columns (1) and (2) of Table 1 identify the nova. Columns (3) and (4) indicate the day of discovery and the apparent magnitude $m_V(t = 0)$ at discovery. It is important to note that many novae are probably discovered some time after visual maximum $m_V$, which occurs $\sim 1$–4 days after the explosion and the 511 keV line emission. To bracket the time during which the explosion must have occurred, we give the date of the last prediscovery observation (or upper limit) in column (5).

Observations during the early decline have been used to estimate the speed class $t_2$, defined as the time necessary for $m_V$ to fall by 2 mag from the discovery value $m_V(t = 0)$ (Table 1, col. [6]). The typical situation is illustrated in Figure 1. Two facts are apparent from the table and the figure. First, the sample of southern novae is likely to be very incomplete. Gaps of greater than 20 days in the coverage of the known novae are common; therefore, very fast novae with $t_2$ of the order of a few days could rise and then fall below the detectable level during such a gap. Warner (1989) estimates that this incompleteness could affect even novae so bright as $m_V \sim 3$. Second, the distance to any nova can only be determined by comparing the apparent magnitude at some known epoch (usually at visual peak) with an absolute magnitude $M_V$. Empirical formulae are available that relate the absolute magnitude $M_V$ to the speed class $t_2$ (Warner 1995). However, the peak $m_V$ is unknown since the time of the peak is unknown, and it can only be estimated by extrapolating back up the prediscovery light curve (Fig. 1, dashed line). Thus the estimated distance $r$ to the nova is a function $r(t)$ of the time before discovery at which the outburst is assumed to occur.

The relationships involved are the well-known distance modulus formula including extinction $A_V$,

$$m_V - M_V = 5 \log r - 5 + A_V,$$

and the extrapolation up the prediscovery light curve,

$$m_V(t) = m_V(t = 0) + \frac{t}{t_2},$$

which can be combined to yield a transcendental relation for the estimated distance $r(t)$,

$$\log r(t) + \frac{A_V(r)}{5} = 1 + \frac{m_V(t) - M_V}{5},$$

if $M_V$ and $A_V(r)$ are given. We solved these equations numerically for each nova during each prediscovery interval using an empirical relation between $M_V$ and $t_2$,

$$M_V = 2.41 \log t_2 - 10.7$$

for $5$ days $< t_2 < 50$ days,

$$= -9 \text{ for } t_2 \leq 5 \text{ days},$$

$$= -6.6 \text{ for } t_2 > 50 \text{ days}$$

(Warner 1995), and the prescription for extinction as a function of celestial coordinates and of distance given by Kil’pio & Malkov (1997). The range of distances given in column (7) of Table 1 for each nova was thus obtained. In all cases the smallest value holds true if the outburst occurred just after the last prediscovery measurement (Table 1, col. [5]), and the largest value corresponds to an outburst occurring at the time of discovery (Table 1, col. [3]). We neglect uncertainties owing to the scatter in the empirical relation equations (eqs. [4]–[6]), which are substantial but still are less important than the uncertainty in the outburst epoch for relatively fast novae such as most of those in Table 1.

| Nova         | Alias | Date of Discovery | $m_V$ at Discovery | Last Prediscovery | $t_2$ (days) | Estimated Distance (pc) | References |
|--------------|-------|-------------------|--------------------|-------------------|-------------|--------------------------|------------|
| Nova Cir 1995 ... |       | 1995 Jan 27.328   | 7.2                | 1995 Jan 12.0     | $\sim 20$   | 2830–4790                | 1, 2, 3, 4 |
| Nova Cen 1995 ... | V888 Cen | 1995 Feb 23.31    | 7.2                | 1995 Jan 27       | $\sim 6$    | 1390–8330                | 2, 4, 5    |
| Nova Sgr 1996 ... | V4361 Sgr | 1996 Jul 11.527  | 10.0               | 1996 Jun 19.631   | 53          | 6660–9810                | 2, 6       |
| Nova Cru 1996 ... | CP Cru  | 1996 Aug 26.98    | 9.25               | 1996 Aug 7.0      | 5.2         | 930–18000                | 2, 4, 7    |
| Nova Sco 1997 ... |       | 1997 Jun 5.09     | 8.5                | 1997 Jun 2.09     | 4.5         | 6830–17740               | 2, 8       |

* Epoch of $m_V = 3$ extrapolated back from discovery. See § 3.1.

References—(1) Liller 1995a. (2) VSNET 1998, available on the World Wide Web at http://www.kusastro.kyoto-u.ac.jp/vsnet/. (3) Greeley, Blair, & Long 1995. (4) F. Bateson 1998, private communication. (5) Liller 1995b. (6) Sakurai 1996. (7) Liller 1996. (8) Liller 1997.
Very little information appears to be available on the abundances of the novae in Table 1. Woodward et al. (1997) have shown that Nova Cru 1996 was definitely of the neon subclass involving an ONeMg white dwarf. More tentatively, enhancement of N but not of O in Nova Cir 1995 (Greeley, Blair, & Long 1995) suggests that it might have occurred on a very massive ONeMg white dwarf (Politano et al. 1995). Since theoretical models (Hernanz et al. 1997; Gómez-Gomar et al. 1998) suggest that the 511 keV line is much more likely to be detectable from neon novae, both of these novae might be promising candidates for detection if they are at the nearer ends of the ranges in column (7) of Table 1.

3. OBSERVATIONS AND ANALYSIS

3.1. Observations

Since launch in 1994 November, the Wind spacecraft has been raised into a complicated and extremely elliptical orbit, most of which is spent outside Earth's magnetosphere. Perigee passes taking the spacecraft within the magnetosphere (and therefore exposing it to high charged particle fluxes in the trapped radiation belts) are brief (typically \( \leq 1 \) day). The overall level of background \( \gamma \)-radiation is therefore relatively low, arising mainly from the cosmic diffuse background and the effects of irradiation by the Galactic cosmic rays.

The TGRS detector is a radiatively cooled 35 cm\(^2\) Ge crystal sensitive to energies between 20 keV and 8 MeV. It is mounted on the top surface of the Wind spacecraft body, which permanently faces the south ecliptic pole; the spacecraft is stabilized by rotation in the ecliptic plane with a 3 s period (Owens et al. 1995). Although the detector is unshielded, some capability for localizing sources exists along the ecliptic plane, since a passive Pb occulter is fixed concentric with the detector and carried around it by the spacecraft's rotation, thereby modulating signals from the rotation plane with a 3 s period (see figures in Teegarden et al. 1996).

The database of regular TGRS background spectra consists of count rates between 20 keV and 8 MeV, which have been accumulated continuously in 1 keV energy bins during 24 minute intervals since launch except for the epochs of perigee passages. The data stream is also interrupted by memory readouts of triggered data from solar flares and \( \gamma \)-ray bursts for periods of \( \sim 2 \) hr (Owens et al. 1995). We summed these spectra into 6 hr intervals, corresponding to the expected timescale of the signal from a classical nova (Hernanz et al. 1997). As noted in § 2 above, it is frequently unclear how much time elapsed between the explosion and the visual discovery for any given nova. We were therefore usually obliged to take 6 hr spectra for the entire period prior to discovery, as far back as the latest available prediscovery observation (Fig. 1, dashed line). Of course, the implied apparent magnitude of the nova brightens as one proceeds back along the light curve, and in some cases this in turn implies that a very bright nova must somehow have escaped detection. We therefore did not consider epochs prior to discovery for which \( m_\nu \), extrapolated according to speed class and corrected for extinction, would have fallen below 3.0 (see Warner 1989).

Two of the novae listed in Table 1 lay in the approximate direction of the Galactic center, near where the Galactic plane crosses the ecliptic, and so were occulted by the Pb occulter (Nova Sgr 1996 and Nova Sco 1997). The TGRS occulted data are returned in four broad 64 channel energy windows, only one of which is binned at 1 keV resolution; this window covers the region 479–543 keV and therefore contains the blueshifted nova line predicted by Leising & Clayton (1987) and Hernanz et al. (1997). For Nova Sgr 1996 and Nova Sco 1997, we summed the occulted spectra over the same prediscovery time intervals as described above for background spectra. We thus expected to have an independent check (by means of location) on any positive signal discovered in the background spectra.

3.2. Analysis of Background Spectra

A characteristic TGRS background spectrum in the range 490–530 keV during a 6 hr interval is shown in Figure 2. The overall features of such spectra, which are very stable from one spectrum to the next, are the following: first, a strong line due to positron annihilation in the spacecraft
TABLE 2

| Line Energy (keV) | Line Width FWHM (keV) | Time from Explosion (hr) | Theoretical Intensity at 1 kpc $^b$ ($\gamma$ cm$^{-2}$ s$^{-1}$) |
|------------------|----------------------|--------------------------|------------------|
| 516 .......       | 8                    | 6                        | 1.6 x 10$^{-2}$   |
| 513 .......       | 8                    | 12                       | 7.8 x 10$^{-3}$   |

$^a$ M. Hernanz 1997, private communication.
$^b$ Hernanz et al. 1997, best-case assumption (model ONe2).

and the passive material surrounding the detector. This line is expected to lie at the exact rest energy 511.00 keV.$^3$ The line shows a clear asymmetry in the form of a broad red wing of instrumental origin. This asymmetry is probably caused by charge collection losses; the increasing effects of radiation damage have caused it to become more pronounced as the mission has proceeded. Second, there is an underlying continuum at energies above and below the background line energy, which over a short range of spectrum may be approximated by a power law. Third, there is a discontinuity in the continuum at the line energy, which is due to incomplete absorption of the line photons in the detector.

The principle behind our analysis was to fit the selected background spectra (see § 3.1) with such components as those described above plus lines fixed at the energies and widths predicted by theory from neon novae. Significant fitted amplitudes in these lines would be taken as detections. The predicted lines are described in Table 2; they correspond to the same annihilation line at two different epochs, 6 and 12 hr after the explosion (Hernanz et al. 1997; M. Hernanz 1997, private communication; Gómez-Gomar et al. 1998). We will refer to these as the “6 hr” and “12 hr” lines, respectively. Note that while the 6 hr line is quite well separated from the background line, the 12 hr line is only blueshifted from it by 2 keV and will thus be badly blended, even with TGRS’s superior energy resolution.$^4$ We thus expect worse statistical and also systematic errors on the 12 hr line. The detection and measurement of the nova line signal (if any) thus depend almost entirely on our results for the 6 hr line.

Fitting the full spectrum shown in Figure 2 with the full complement of model components (background 511 keV Gaussian line, nova 6 or 12 hr Gaussian line,$^5$ power law, and step function at 511 keV) does not lead to acceptable values of $\chi^2$ (e.g., $\approx$ 500 for 35 dof in Fig. 2). The main reason for this is the asymmetric shape on the red side of the background 511 keV line, which is apparent in Figure 2, whose origin is unclear. It became more pronounced as the mission proceeded and was therefore probably caused by accumulated radiation damage; an investigation of this effect is in progress (Kurczynski et al. 1999).

Although the anomalous red component of the background 511 keV line is not perfectly understood, this is not of crucial importance to our search for excess emission on the blue side of the profile. We have found that the best fits are obtained when a simpler model (background 511 keV line, nova 6 or 12 hr line, and constant approximation to the 6 hr line).

The instrument gain has varied slightly (by $\sim$0.5%) during the mission. For the purpose of measuring line positions close to 511 keV, we can use the position of this background annihilation line as a reference energy to correct this gain shift. The procedure involved—fitting a Gaussian line and equating the position of its peak to 511.00 keV—is described by Harris et al. (1998).

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$^4$ As measured by Harris et al. (1998), the FWHM energy resolution of TGRS at energy 511 keV degraded during the mission from 3.2 keV to greater than 4 keV because of radiation damage from cosmic-ray impacts; this loss of resolution appears to be due to the growth of red wings on spectral lines as described below.

$^5$ The fits are not strongly sensitive to the precise line shape, so long as the FWHM is fixed at 8 keV (Table 2). For example, Leising & Clayton (1987) argued in favor of the broad flat-topped line shape expected from the near side of an expanding shell. We tested this line shape and found little difference from results obtained with the Gaussian shape that M. Hernanz (1997, private communication) used as an approximation.
power law) is fitted to energies ≥ 511.0 keV only (Figs. 3a and 3b). The values of \( \chi^2 \) for such fits typically lie between 15 and 25 for 17 dof.

In detail, our method of fitting each spectrum was to vary the model parameters until the count rate was best reproduced according to the minimum of \( \chi^2 \); errors were calculated by the method of Lampton, Margon, & Bowyer (1976) for mapping the range of parameter space where the minimum \( \chi^2 \)-value is exceeded by 1. The line amplitudes from the count rate were normalized by the detector effective area (a function of the direction to the nova), which is known from Monte Carlo simulations (Seifert et al. 1997). In Figure 3b (dotted line), we use this detector response to show that a neon nova with the theoretically expected properties would be easily detectable at a distance of 1 kpc.

A typical series of fitted amplitudes for the 6 hr line, during times when Nova Sco 1997 may have erupted, is shown in Figure 4a. Three features of this result call for attention. First, the points are distributed about a mean value in a way consistent with random scatter (\( \chi^2 \) dof\(^{-1} = 0.71 \)). Second (consistent with this), there is no individual point of high significance relative to the mean such as would be expected from a real nova line. Third, the mean value is not zero—there is a systematic positive nova line amplitude.

The systematic positive amplitude is probably due to a systematic departure of the background 511 keV line from a Gaussian shape on its blue wing (for example, if the anomalous red component seen in Fig. 2 has a Gaussian shape, its blue tail would effectively contribute such a constant value to the nova line). We have found in all cases that the systematic positive offset is very stable. It has increased slowly during the mission; the timescale of the increase (~ months to years) is much longer than the timescales (~ 10 days) over which we search for lines from a given nova. In this respect the behavior of the positive offset is very similar to that of other measures of degradation of detector performance, such as energy resolution (Harris et al. 1998) and the amplitude of the anomalous red component seen in Figure 2.

Apart from this stable and well-behaved offset (which can be removed from the nova line flux by simple subtraction), there appear to be few or no systematics in our nova line measurements made from background spectra. We therefore believe that single significant positive measurements (following subtraction of the systematic offset) would be valid evidence for short-lived (~ 6 hr) line emission. We now turn to two internal checks that could be made on such a detection. In § 3.3 we examine the usefulness of data modulated by the TGRS occulter for some celestial directions. In

![Image](image-url)
§ 3.4 we show that small improvements in sensitivity can be obtained from measuring the 511 keV line at epochs subsequent to its peak flux at $t = 6$ hr (what we have called the 12 hr line).

3.3. Analysis of Occulted Spectra

The Pb occulter referred to in § 3.1 subtends an angle of 90° along the ecliptic and approximately 16° across it and is 1 cm in thickness. The spectra in 64 1 keV energy channels around 511 keV, when modulated with a 3 s period by the occulter, are binned into 128 angular channels ("sectors") of 2'8125 in ecliptic longitude. We obtained spectra for Nova Sgr 1996 and Nova Sco 1997 by fitting occultation dips centered on the respective ecliptic longitudes ($\lambda = 275\degree.66$ and 268\degree.73) to each energy channel (see Teegarden et al. 1996; Harris et al. 1998). A typical spectrum for a 6 hr period is shown in Figure 5.

All background features varying on timescales greater than 3 s are subtracted out of such a spectrum, notably the 511 keV background line that is so prominent in Figure 2. The subtraction is very effective, and the residual spectrum in Figure 5 is almost featureless. For occultations having a phase close to that of the Galactic center ($\lambda = 266\degree.8$), the strongest feature in the residual spectrum is expected to be the diffuse Galactic 511 keV annihilation line (see, e.g., Purcell et al. 1997). However, the measurement by Harris et al. (1998) with the TGRS occulter during 90 day intervals indicates that during 6 hr intervals this line will be detected at a level of only $\sim 0.35 \sigma$.

We therefore fitted the occulted spectra between 490 and 530 keV by a model containing two lines, one at exactly 511 keV arising from the diffuse Galactic source, and one at either the 6 or 12 hr line energy (Table 2). The gain-corrected 511 keV line positions were taken from the corresponding background spectra (see § 3.2, footnote 2). The 511 keV line widths were fixed at the values measured by Harris et al. (1998) during 90 day intervals containing the nova epoch.

Results from a single 6 hr period for the 6 hr line in Nova Sco 1997 are shown in Figure 5 (solid, dashed, and dot-dashed lines); in Figure 6 we show the time series of all such fits for this nova. Although there do not appear to be any large systematic effects, it is immediately apparent that some of the 6 hr intervals exhibit anomalously large errors. These situations occur in a model that possesses multiple minima of $\chi^2$ lying close to each other in the model's parameter space. The region defined by $\chi^2 + 1$ is then much larger than would naively be expected from the behavior of $\chi^2$ in the region around the true minimum. In the present case, which is a two-line model in which the lines are not well resolved, such situations tend to arise when the spectrum is best fitted by lines with amplitudes of opposite signs. We found this to be true of the badly behaved fits in Figure 6.

3.4. Combination of 6 and 12 Hour Line Results

The time series of background spectrum fit results for Nova Sco 1997 are shown in Figure 4a for the 6 hr line and in Figure 4b for the 12 hr line. We see that the statistical errors on the 12 hr line are generally much larger, as expected, because of worse blending with the 511 keV background line. The systematic positive offset described in § 3.2 for the 6 hr line is also worse in the 12 hr line flux measurement.

The 6 and 12 hr line fits are independent and can be combined so as to improve the significance of a detection in one of them. In our simple approximation, they are combined with a weight proportional to their contribution to the Hernanz et al. (1997) light curve (see Table 2) and proportional to the inverse square of the statistical error in the usual way. Each 6 hr line measurement (Fig. 4a) is combined with the 12 hr line measurement from the following 6 hr interval (Fig. 4b). The results for Nova Sco 1997 are shown in Figure 4c for background spectrum fits.6

It is clear from Figure 4b that the quality of the 12 hr line measurements is much worse than that of the 6 hr lines, as expected. Thus the 12 hr line measurements yield only a small gain in the sensitivity of the line search when combined with the 6 hr line measurements, which contain most

6 In this figure, and from here onward, the positive offset in these measurements is subtracted off.
4. RESULTS

Our results for Nova Cir 1995, Nova Cen 1995, Nova Sgr 1996, and Nova Cru 1996 are shown in Figures 7–10. For Nova Sgr 1996 there are both background and occulted spectra (Figs. 9a and 9b), for the others only background spectra. The results are given as the nova line flux at all epochs when the thermonuclear outburst could have occurred; note that (as derived in § 2) the theoretical value with which they are compared is time-dependent (Figs. 7–10, dotted line). The positive systematic offsets described in § 3.2 have been subtracted. In the absence of any single strong positive 6 hr line detections, we have combined the 6 and 12 hr line results as described in § 3.4.

Once the positive offset has been removed, the distribution of the measured line intensities is quite free from systematics, as previously deduced from the Nova Sco 1997 results (§ 3.2 and Fig. 4c). The distribution of the complete ensemble of measurements (264 points) agrees very well with a random distribution about zero. We therefore conclude that none of the novae in our sample emitted the expected blueshifted 511 keV line down to a limiting flux that varied for each nova. We express this limit conservatively as the 3σ upper limit from the statistical errors on each 6 hr point; it is represented by dashed lines in Figures 4c and 7–10, and the mean values for each nova are given in Table 3. The mean values vary slightly from nova to nova partly because of the slow degradation of detector performance (§ 3.2), but mainly because of the variation of effective area with angle of incidence of the nova in the detector.

The typical 3σ sensitivities in Table 3 may be compared with the prediction of $1.6 \times 10^{-2}$ photons cm$^{-2}$ s$^{-1}$ for a neon nova at 1 kpc (Table 2). From this we derive our most important conclusion, namely that the TGRS measurements are sensitive enough to detect neon novae to a distance of

![Fig. 7](image-url)  
Fig. 7.—Measured fluxes for Nova Cir 1995 in the 6 hr nova line (combined with 12 hr measurement as described in § 3.4) from background spectra. Symbols as in Fig. 4c. Dashed line: 3σ upper limits on flux. Dotted line: Predicted flux from the nova parameters in Table 1 and the Hernanz et al. (1997) ONe2 model.

![Fig. 8](image-url)  
Fig. 8.—Measured line fluxes for Nova Cen 1995. Symbols as in Fig. 7.

![Fig. 9](image-url)  
Fig. 9.—(a) Measured line fluxes for Nova Sgr 1996 from background spectra. Symbols as in Fig. 7. (b) Measured line fluxes for Nova Sgr 1996 from occulted spectra.
about 2.5 kpc at 3 \sigma significance, for favorable estimates of the nova line emission (Hernanz et al. 1997, model ONe2).

There remains a small possibility that a 511 keV line event associated with one of the novae has been missed because of incomplete coverage. It can be seen from Figures 4 and 10 that losses of entire 6 hr intervals are rare, generally involving perigee passes of \( \leq 1 \) day (Figs. 7, 8, and 10). Brief losses of data within a few 6 hr intervals cause larger than normal error bars and arise when TGRS’s operation mode changes following a \( \gamma \)-ray burst trigger or from telemetry errors. Overall, we estimate that the instrument’s live time.

\[ \phi_{\text{pred}} = 0.016/r(t)^2, \]

where the distance \( r(t) \) in kpc is obtained from equation (3). Note that \( \phi_{\text{pred}} \) is not a light curve; as shown in Table 1, there is usually a wide range of allowed explosion times, and \( \phi_{\text{pred}} \) is the predicted flux at any one time of explosion. In two cases (Nova Sco 1997 and Nova Sgr 1996; Figs. 4c and 9a) the predicted flux is always below our 3 \sigma upper limit for any of the allowed explosion times; these novae must be too distant for our results to be used to constrain even the most optimistic nova model (Hernanz et al. 1997, model ONe2).

The other three novae (Nova Cir 1995, Nova Cen 1995, and Nova Cru 1996) are predicted to yield a detectable \( \phi_{\text{pred}} \) only if the explosion occurred early in the allowed range of times (prior to \( \sim 12 \) days before discovery for Nova Cir [Fig. 7], 7 days before discovery for Nova Cen [Fig. 8], and 9 days before discovery for Nova Cru [Fig. 10]). In other words, the allowed range of distances for these novae includes the TGRS detection limit \( \sim 2.5 \) kpc. The ONe2 model can be tested using our results for these novae if further investigations yield either the appropriate constraints on explosion time or an independent measurement of the distance to the nova.

5. DISCUSSION

5.1. Results for Individual Novae

As emphasized in § 2, it is very difficult to use our results for the individual novae to constrain the ONe2 model because of our lack of knowledge of two related nova parameters, the epoch of explosion and the distance. In Figures 4c and 7–10, we use the limited information given in Table 2 to plot the predicted fluxes \( \phi_{\text{pred}} \) as dotted lines, which depend on the time relative to discovery according to

\[ \phi_{\text{pred}}(t) = 0.016/r(t)^2, \]

where the distance \( r(t) \) in kpc is obtained from equation (3). Note that \( \phi_{\text{pred}} \) is not a light curve; as shown in Table 1,

![Fig. 10.—Measured line fluxes for Nova Cru 1995. Symbols as in Fig. 7.](image-url)
that ~ 2% of Galactic novae occur within 2 kpc of the Sun in the southern hemisphere. Moderate estimates of the global nova rate ~ 50 yr^{-1} then imply that TGRS would detect one neon nova during ~ 3 yr; higher global rates, or a higher fraction of neon novae, would imply more detections.

Further papers in this series will utilize this search strategy and will follow up the possibilities arising from detailed study of the already known novae as described in the previous section.

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