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POSITRON ANNIHILATION GAMMA RAYS FROM NOVAE

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ABSTRACT

The potential for observing annihilation gamma rays from novae is investigated. These gamma rays, a unique signature of the thermonuclear runaway models of novae, would result from the annihilation of positrons emitted by β^+-unstable nuclei produced near the peak of the runaway and carried by rapid convection to the surface of the nova envelope. Simple models, which are extensions of detailed published models, of the expansion of the nova atmospheres are evolved. These models serve as input into investigations of the fate of the emitted positrons and transfer of the resulting gamma-ray photons. The resulting estimates suggest that nearby Galactic fast novae could yield detectable fluxes of electron-positron annihilation gamma rays produced by the decay of ^{13}N and ^{18}F. Although nuclear gamma-ray lines are produced by other nuclei, it is unlikely that the fluxes at typical nova distances would be detectable to present and near-future instruments.

Subject headings: elementary particles — gamma rays: general — nucleosynthesis — stars: novae

I. INTRODUCTION

In view of recent developments in the understanding of novae and in gamma-ray astronomy, we evaluate the potential of observations of positron annihilation gamma rays as diagnostics of novae. We follow the suggestion of Clayton and Hoyle (1974) but extend their ideas in a somewhat more quantitative manner. Important developments include improved models of the classical nova phenomenon, improved estimates of the nucleosynthesis expected to occur in novae, the recognition of a new class of nova events, the demonstration of the astronomical usefulness of the long-term gamma-ray data base of the *Solar Maximum Mission* gamma-ray spectrometer, and the approaching launch of the Gamma-Ray Observatory.

We present here time-dependent calculations of the emerging gamma-ray fluxes resulting from electron-positron annihilation in the expanding atmospheres of novae. We also evaluate the fluxes of nuclear decay gamma rays from positron emitters produced in novae. We adopt the now standard thermonuclear model of the classical novae, which consists of a thermonuclear runaway in the accreted hydrogen-rich atmosphere of a white dwarf in a binary system (Starrfield, Truran, and Sparks 1978, hereafter STS, and references therein). The positrons result from the weak decay of proton-rich nuclei created during the runaway by capture of ambient protons on nuclei mixed upward from the white dwarf core. It is the power from those decays that makes possible the ejection of a substantial fraction of the envelope. We are motivated to this investigation by the active climate for gamma-ray astronomy that now exists and by the hope that the common nova may prove to be a directly measurable example of thermonuclear-powered hydrodynamics.

The calculation of Clayton and Hoyle (1974) was highly simplified, so we have attempted improvements to better describe the nova as a spectroscopic target. We employ a simplified hydrodynamic model of the expansion of the heated atmosphere. This gives a more credible time dependence to the gamma-ray luminosity from the shortest-lived emitters than does a constant velocity expansion. It also yields the physical conditions, i.e., temperature and density, of interest for determining the mode of annihilation of the positrons. These quantities determine the fraction of the annihilations which result in line photons as opposed to an orthopositronium continuum, and the broadening of the line due to thermal Doppler shift. We treat the propagation of the photons through the atmosphere with a Monte Carlo simulation. This yields the emissivity of the surface and the emerging energy spectrum. We use the results of much improved nuclear reaction networks (Wiescher *et al.* 1986; Hoffman and Woosley 1986) which more accurately identify the abundances of the radioactive nuclei, specifically the potentially important ^{18}F nucleus omitted by Clayton and Hoyle. We call attention as well to the importance of a reliable treatment of convection in the nova atmosphere and a complete treatment of the nova phenomenon, coupling the dynamics to an updated nuclear reaction network. Finally, we can place these predictions in the context of data bases existing and planned.

II. HYDRODYNAMIC SIMULATION

A reasonably complete hydrodynamic history of the heating and subsequent expansion of the nova atmosphere requires an elaborate numerical calculation (e.g., Starrfield, Sparks, and Truran 1986; Prialnik 1986). The hydrogen-rich component is accreted from a companion star in a close binary and mixed with the hydrogen-exhausted component of the white dwarf. Electron degeneracy sets in in this atmosphere as it settles down and grows in mass, until at some point the hydrogen-burning reactions initiate a thermonuclear runaway of the type associated with degeneracy-lifting instability. Convection rapidly heats the entire envelope as it mixes the material in the burning zones upward, carrying those radioactive nuclei with lifetimes longer than the convective turnover time toward the nova photosphere. This entire scenario has numerous theoretical uncertainties that nonetheless require numerical treatment. For the problem we treat in this paper, however, it would appear that a simpler treatment contains the essence of the more complete ones. We need only a reasonably accurate time-dependent history of the nova ejecta. We therefore construct a simplified hydrodynamic model of the expansion of the envelope, taking as our initial conditions the expected state of the envelope following the thermonuclear runaway and rapid convective mixing. Our simple arguments generate a description in substantial agreement with more complete numerical histories. This approach can be summarized as follows.

We begin with the envelope in place on the white dwarf, at a time just following the peak of the runaway and the violent turnover of the envelope. The masses of the dwarf and the envelope are chosen to correspond to those of particular published models of Starrfield, Sparks, and Truran (1974, hereafter SST) and STS. The radius of the white dwarf (the inner edge of the envelope) is considered fixed throughout these calculations. We assume that the structure of the envelope at the time the temperature in the shell source peaks is that of a radiation-dominated polytrope with $P \propto \rho^{4/3}$, and that the envelope is in hydrostatic equilibrium. We take the temperature at the base of the envelope to be the peak temperature attained in the published model and choose the outer radius to be that appropriate to the same time in the particular model of SST or STS. Now the density of the envelope is determined throughout, as is the structure of the envelope. While the assumptions which lead to this structure might well be questioned, our purpose, to start with a reasonable distribution of matter in the potential well of the star, is served. After this stage of the outburst it is the gravity of the star and the stored energy of the β^+-emitters which dominate the evolution of the outer layers. We divide the envelope into discrete mass shells and follow numerically the dynamic effects caused by the presence of the radioactivity, which simply decays freely from this time, heating the envelope and accelerating the outer layers of it to escape velocity. We emphasize that we do not attempt to improve upon existing nova models but only wish to obtain the explicit time dependence of the physical quantities of interest for the gamma-ray emission problem.

The expansion of the envelope is followed by evaluating for each mass zone, in a given time step, the acceleration from the momentum equation (due to the excess of the pressure gradient over the hydrostatic value), the velocities and positions of the zone interfaces at the middle and end (respectively) of the time step due to the acceleration, and finally the resulting thermodynamic conditions from an energy equation which includes heating and cooling due to expansion and contraction, radioactivity, and energy flow from adjacent zones. We approximate the differential equations which govern the dynamical evolution with finite-difference equations and follow them in time in an explicit fashion (e.g., Cox and Giuli 1968). The pressure includes only particle and radiation pressures, since degeneracy has effectively been lifted by the time we begin the evolution. The flow of heat across the boundaries is assumed to be entirely radiative and given by the diffusion approximation. The opacity is taken to be that due to electron scattering, which is the dominant source, plus a Kramers-type opacity to account for the great increase in opacity for certain regions of the ρ-T plane. We neglect the convective luminosity in the subsequent evolution. Rapid convection is an essential, in fact necessary, aspect of such nova models, but it should not be too important for most of the times we treat here, when the convection zone rapidly recedes from the surface (Prialnik 1986). It is most extensive prior to and just after the time of peak temperature, when in addition to transporting heat outward it carries the stored energy of the positron emitters to the outer layers. This important effect of convection we do include, in that we begin our simulation with the radioactivity mixed throughout the envelope material.

We obtain the outer boundary conditions on temperature and pressure by assuming that the temperature in the atmosphere obeys the static, gray-atmosphere solution to the equation of transfer. The temperature and pressure outside the outer boundary of the outermost zone, which are needed to compute the emerging luminosity and the acceleration of the outer boundary, are thus calculated at optical depth zero from the effective temperature. All the relevant quantities are calculated for each zone of fixed mass at discrete time steps which are restricted by the usual Courant condition. We thus follow the expansion until the density of positrons in the surface layers falls below a level which is interesting in terms of emission of annihilation gamma rays.

III. ABUNDANCE OF POSITRON EMITTERS

The initial abundance of positron emitters in the envelope is a crucial factor in determining the resulting gamma-ray emission. Beyond the fact that the emissivity per unit mass increases with increasing abundances, the additional energy released by more abundant positron emitters drives the expansion to higher velocities after the peak of the runaway, exposing the envelope material faster. In their models, SST and STS followed the abundances of nuclear species up to mass 17, which includes the dominant nuclei regarding energy generation. For heavier isotopes which are of interest for gamma-ray emission because of their relatively long lifetimes, we must use estimates from parametric nucleosynthesis studies. The most up-to-date of such studies are those of Wiescher *et al.* (1986) and Hoffman and Woosley (1986). They report the abundances of some 30 nuclear species resulting from hydrogen burning in matter with initial composition and peak temperature given by particular nova models of STS. Such results are uncertain because, in addition to uncertainties in some of the nuclear cross sections, they do not account for the fact that at any given time material in a nova envelope experiences a range of temperatures and that convection can rapidly mix material with composition characteristic of a particular temperature to regions with very different temperatures. Thus fragile nuclei which are more effectively produced at higher temperatures, and which would not long survive at those temperatures, can survive if they are carried to cooler regions by convection (see, for example, the discussion of Prialnik [1986] concerning ^{15}N).

The enrichments of the CNO isotopes in the prenova envelope are not arbitrary. A certain degree of enhancement is necessary to achieve the rapid ejection of matter. This is clearly shown in the nova model studies mentioned above. The observations of elemental abundances in nova ejecta is generally consistent with the expected enrichments, and is summarized in Wiescher *et al.* (1986). The mechanism of such enrichments is thought to be the mixing of white dwarf core material into the envelope. Prialnik and Kovetz (1984), Kovetz and Prialnik (1985), Prialnik (1986), and Woosley (1986) have found that diffusion due to the core-envelope composition gradient and resulting convection can enrich the region which subsequently undergoes thermonuclear burning to the levels required by the models and implied by observations. For fast novae it is likely that, in order to achieve observed ejection velocities and super-Eddington luminosities, the abundances of the positron emitters in the outer envelope must be significant.

Table 1 shows some characteristics of the β^+-emitting nuclei that are of interest. The isotopic distribution of these depends most strongly on the peak temperature achieved in the burning. We use the final abundances of the daughters of the

TABLE 1

CHARACTERISTICS OF POSITRON-UNSTABLE NUCLEI

Isotope	Mean Lifetime	γ-Ray Energy (MeV)	Average β^+ K.E. (MeV)
^{13}N	862 s	...	0.5
^{14}O	102 s	2.31	0.8
^{15}O	176 s	...	0.7
^{17}F	93 s	...	0.8
^{18}F	158 minutes	...	0.2
^{34m}Cl	46 minutes	0.15(47%)	2.2(47%)
		1.18(13%)	1.2(28%)
		2.13(41%)	0.6(24%)
		3.30(11%)	

CNO nuclei given by SST and STS for the two particular models of theirs which we simulate, which are further described below, as the abundance at peak temperature of the parents. These abundances are given along with other relevant quantities regarding the models in Table 2. Heavier species may also be of interest for their gamma-ray emission. These include ^{18}F, possibly ^{34m}Cl, and the long-lived species ^{22}Na ($\tau = 3.75$ yr) and ^{26}Al ($\tau = 10^6$ yr). The latter two will not contribute to the early annihilation radiation which is the subject of this work, but they might contribute to the diffuse Galactic positron annihilation feature and provide observable nuclear gamma-ray line emission.

Under suitable conditions ^{18}F might be produced from ^{16}O. At the temperatures relevant to the burning regions in most novae, the reaction ^{16}O$(p, \gamma)^{17}$F occurs. When the temperature is sufficient ($T_8 > 2$), another proton capture produces ^{18}Ne, which quickly decays to ^{18}F. At these temperatures, ^{18}F is largely destroyed by ^{18}F$(p, \alpha)^{15}$O. Convection can potentially carry the hot, ^{18}F-rich matter to cooler regions where the ^{18}F survives. Alternatively, in some nova models temperatures of $T_8 = 2$ are never reached, but if the temperature remains high long enough, after much of the ^{17}F decays to ^{17}O, the subsequent reaction ^{17}O$(p, \gamma)^{18}$F produces the positron emitter. A discussion of the temperature dependences of the abundances of various species can be found in Wiescher *et al.* (1986), who simulated its effects in a simple way in a similar parametric study. We will simply use a mass fraction of ^{18}F, $X(^{18}\mathrm{F}) = 10^{-3}$, at the start of our simulation, since that is very close to what the above authors find for the resulting ^{18}O both for a low-temperature model (Wiescher *et al.* 1986), where the effect of convection is ignored (but should not be dramatic regarding ^{18}F production), and for higher temperature models which include the effect of convection (Hoffman and Woosley 1986).

Another potentially interesting nucleus is ^{34m}Cl, the isomeric state of ^{34}Cl at 0.146 MeV. The relatively long lifetime and accompanying nuclear emission of the ^{34m}Cl beta decay (see Table 1) make it a possible source of observable gamma-ray emission, if it is produced in sufficient quantities. Hoffman and Woosley find that ^{34}S, the daughter of ^{34}Cl, can possibly be produced in mass fraction exceeding 10^{-3}. How much of this might have its parentage in ^{34m}Cl depends on the capture path followed in the burning. We make the arbitrary assumption that the initial mass fraction (at the time of peak T) of ^{34m}Cl is $X(^{34m}\mathrm{Cl}) = 10^{-4}$, to see what if any observable effect it might yield.

Of course, the resulting abundances of all these nuclei depend on the abundances of their seeds before the burning. The observations of a newly recognized class of nova events which produce ejecta rich in neon and heavier elements, and might be interpreted as runaways on O-Ne-MG white dwarfs (See Wiescher *et al.* 1986; Starrfield, Sparks, and Truran 1986), enhance the possibility that the heavier isotopes discussed here could be observed via gamma-ray emission.

IV. POSITRON ANNIHILATION

Now we seek to determine the mode of annihilation of the positrons—whether they annihilate directly, and at what energy (whether the line photons are Doppler-shifted), or annihilate via the formation and decay of positronium.

The spectra of the positrons emitted by the nuclei of interest here have endpoint energies ranging from 0.6 to 4.5 MeV. Positrons entering a gaseous medium at these energies are quickly slowed by ionizing collisions with neutral atoms and by long-range Coulomb interactions with any ionized component. The energy loss of the positrons is essentially the same as that of fast electrons, except for the possibility of annihilation. For much of the time of the nova evolution we follow, the matter of the outermost part of the envelope is predominantly ionized, so the Coulomb interactions dominate. The positrons can annihilate in flight before being slowed to thermal energies, annihilate directly with electrons when both are at thermal energies, or form positronium at thermal energies (or at greater than thermal energies if positronium formation occurs via charge exchange with neutrals). Free annihilation of electron-positron pairs produces two 0.511 MeV photons in the rest frame of the center of mass of the pair. Annihilation of positrons at higher than thermal energy will thus yield a Doppler-shifted continuum above 0.25 MeV, not a line. Those positrons which annihilate directly at thermal energies produce a line broadened by thermal and radial motions. Positronium decay from the ground state yields two 0.511 MeV photons if from the singlet spin state, or a three photon continuum below that energy if annihilation occurs from the triplet spin state, which it does three-quarters of the time, in the laboratory. The triplet state lifetime against annihilation is more than 10^3 times as long as the singlet state, so that its decay can be prevented by collisions with ambient particles or photons, or by exchange of electrons of opposite spins, when the singlet decay can still occur. We estimate the likelihood of

TABLE 2

NOVA MODEL PARAMETERS

Model	Envelope Mass ($M_\odot$)	Peak Temperature (10^8 K)	Initial CNO Composition	Abundances in Ejecta (per 10^3, by mass) ^{12}C	^{13}C	^{14}N	^{15}N	^{16}O	^{17}O
1(SST 7)	10^{-3}	2.2	12%	3.0	10.3	22.1	43.2	27.4	9.3
2(STS 4)	10^{-4}	1.5	45%	130	230	120	1.0	7.1	0.1

these various effects in order to evaluate the luminosity in the annihilation line.

We treat the energy loss of the positrons as identical to that of electrons. Their energy loss per unit length is written as

$$-\frac{dE}{dx} = 4\pi n_e \frac{e^4}{mv^2} \ln B , \tag{1}$$

where n_e is the electron density, v is the velocity of the positron, and B is the ratio of the maximum impact parameter to the distance of closest approach. The value of the logarithm depends on the specific interaction processes considered, but varies by only a factor of 2 or 3 for most applications. We employ a rather standard value for energy loss in an electronic plasma including both close collisions and long-range collective plasma interactions (e.g., Jackson 1975). We calculate the probability of annihilation in slowing from initial energy E_0 to thermal energy $E_{\rm th}$:

$$P(E_0) = \int_{E_0}^{E_{\rm th}} n_e \sigma_a(E) \left(\frac{dE}{dx}\right)^{-1} dE , \tag{2}$$

where we use for the annihilation cross section, σ_a, the expression which assumes the Born approximation (e.g., Heitler 1962). We find that this probability reaches only 3% for the most energetic positrons (from ^{34m}Cl) and is $<1\%$ for positrons emitted by ^{13}N and ^{18}F. We also estimate the range of the positrons in the envelope, in order to evaluate the rate of escape of positrons to see whether novae can make a significant contribution to the positron content of the interstellar medium. The ranges of the positrons emitted by the nuclei of interest here are typically 0.1 g cm^{-2} for the composition of model 1, and 50% greater for model 2.

Positronium formation and annihilation have been investigated in detail by Crannell *et al.* (1976) for annihilation of positrons produced in solar flare events. The problem is quite complex even in treating only a single temperature and density. Since both change rapidly (with time and depth) in the expanding nova atmosphere, we make simplifying assumptions to estimate the reduction in the line flux due to orthopositronium annihilation. Crannell *et al.* (1976) find that free annihilation dominates positronium formation at temperatures above 10^6 K. At temperatures below 10^5 K, the rate of radiative formation of positronium exceeds the direct annihilation rate, and at temperatures low enough for the existence of neutral hydrogen the rate of formation of positronium via charge exchange exceeds those of both radiative capture and direct annihilation. For most of the evolution of the nova atmosphere of interest here, positronium formation will dominate direct annihilation. The important question is then how much of the positronium formed annihilates via the singlet state as opposed to the triplet state.

We simply assume that 90% of the thermalized positrons form positronium in the statistical ratio of 3:1 for the spin states and 10% annihilate directly, yielding two line photons. The total line intensity relative to the continuum then depends on the probability that triplet positronium is destroyed in the 1.4×10^{-7} s before its annihilation. Because the reactions for the formation and destruction of positronium are fast compared with the rate of positron production, we assume that equilibrium between the production and destruction of each spin state exists. We also assume that the positrons which form positronium do so immediately upon emission, and that any positronium broken up by particle or photon interactions is immediately re-formed in the statistical ratio of spins. This latter assumption is not strictly correct because some of the liberated positrons will undergo direct annihilation. We account for them in the assumption that 10% of all thermalized positrons annihilate directly. We write the equilibrium between production and decay of the two spin states as

$$\frac{1}{4}\left[\frac{dn}{dt} + (n_1 + n_3)\lambda_b\right] + n_3 \lambda_c = n_1(3\lambda_c + \lambda_1 + \lambda_b) , \tag{3}$$

$$\frac{3}{4}\left[\frac{dn}{dt} + (n_1 + n_3)\lambda_b\right] + 3n_1 \lambda_c = n_3(\lambda_c + \lambda_3 + \lambda_b) , \tag{4}$$

where dn/dt is the rate of formation of new positronium, n_1 and n_3 are the numbers of positronium atoms in the singlet and triplet states, λ_1 and λ_3 are the rates of annihilation of the singlet and triplet states, λ_b is the rate of breakup of positronium due to collisions and photodissociation, and λ_c is the rate of ortho-para conversion by the exchange of free electrons of the opposite spin. Solving for the ratio of triplet decays to singlet decays, we obtain

$$\frac{I_3}{I_1} = \frac{n_3 \lambda_3}{n_1 \lambda_1} = \frac{3\lambda_3}{\lambda_1} \frac{4\lambda_c + \lambda_1 + \lambda_b}{4\lambda_c + \lambda_3 + \lambda_b} , \tag{5}$$

and the fraction of positronium-forming positrons which yield two 0.511 MeV photons is

$$f_2 = \frac{1}{1 + (I_3/I_1)} . \tag{6}$$

We use rather simple expressions for the rates of the various interactions. For the collision and photon ionization processes we use the rates of the corresponding processes on hydrogen atoms (e.g., Seaton 1960), correcting for the ionization potential of 6.8 eV of positronium. The process of conversion between the ortho and para spin states of positronium has been treated by Baltenko and Segal (1983). They find that in the limit of low electron energy the cross section for this process is

$$\sigma_c = 6.4 \times 10^3 \pi a_0^2 , \tag{7}$$

where a_0 is the Bohr radius, and that for an electron temperature of 1.0 eV the decay of triplet positronium is effectively inhibited at densities above 10^{12} cm^{-3}. We use this cross section, even though it is valid only for very low electron energies, because its effect is important only at late times when the temperature approaches 1.0 eV in the outer envelope. Before that time, triplet decay is inhibited by photodissociation as long as the photon temperature is 2×10^4 K or greater. We may still be overestimating the effect of ortho-para conversion, however, by using this large value for the cross section. We obtain the free electron density from the Saha ionization equilibrium condition, where we treat the matter as hydrogen and nitrogen (to represent everything besides hydrogen for simplicity), and take into account that only half the free electrons have the appropriate spin for a given transition.

V. GAMMA-RAY ESCAPE

Given the emissivity per unit mass in the annihilation line and positronium continuum, the emerging intensity of gamma rays then depends on the transfer and escape of the emitted photons. This atmosphere is extremely thick to Compton scattering, so the emerging gamma-ray spectrum, which is mostly produced in the outer few scattering lengths, will contain an additional scattered continuum. We estimate the spectrum and intensity of the emergent radiation with a Monte Carlo simulation of the photon scattering. We follow the history of each of 10^5 photons which originate in the outer several scattering mean free paths. The initial energies of the photons are chosen at the line energies (annihilation or nuclear decay) or in the positronium continuum, according to their relative probability of emission. The input orthopositronium spectrum is that given by Ore and Powell (1949). The nature of the scattering events is determined to be Compton scattering or photoelectric absorption on K-shell electrons of heavier elements, according to the relative probabilities of the two. Regarding photoelectric absorption, we treat all heavy elements as nitrogen (in the abundance of all CNO elements) and iron (in its solar abundance). All photons are followed until they are absorbed, fall below the energy threshold (taken to be 50 keV), or escape the envelope. The energies of escaping photons are recorded in bins of 5 keV width.

VI. RESULTS

We use as our starting point two models of fast novae with two different envelope masses at runaway, model 7 of SST and model 4 of STS, here called models 1 and 2, respectively. We choose these particular models because they are representative of the many computed models of the two mass ranges and there are more published details regarding their evolution for comparison with our simpler simulation of the expansion. Some details of these models are listed in Table 2.

Model 1 is designed to simulate model 7 of SST, a 1 $M_\odot$ white dwarf with a 2.5×10^{30} g envelope enriched with core C and O so that CNO nuclei comprise 11.6% of the mass of the envelope. From the final abundances in Table 2 we see that the total number of these nuclei is conserved, but they are isotopically rearranged by the burning at high temperature, which peaked at $T_8 = 2.2$. Our model begins with these quantities taken from SST, with the radioactive progenitors of the CNO isotopes in the final abundances of their daughters (i.e., 1% ^{13}N, 2.2% ^{14}O, and so on) and evenly distributed throughout the envelope. When the peak temperature is first reached in this model of SST, the outer radius is 10^9 cm. They find that the abrupt temperature increase produces a shock wave which accelerates the outer envelope to high velocity but not escape. The overexpanded outer layers collapse rapidly until halted by the release of gravitational energy. When the oscillations are damped, the outer radius is 6.5×10^9 cm. To avoid complexities introduced by the shock, we begin with the envelope at this radius, which is also when the temperature begins to decline from its peak value. Integrating the gravitational and thermal energies over polytropic envelopes, as discussed above, for outer radii of 8×10^8 and 6.5×10^9 cm, we find that 3.5×10^{47} ergs have gone into raising the envelope to our initial configuration. This energy can just about be accounted for by the conversion of ^{12}C to the ensemble of positron emitters we begin with (1.5×10^{47} ergs after subtracting neutrino losses) and the production of 2% He by mass (2×10^{47} ergs). These remain 3.3×10^{46} ergs stored in the positron emitters (after neutrino losses), and we add 2×10^{46} ergs to the bottom zone to account for further prompt energy generation. We can only justify these choices by comparing our results with the detailed model of SST.

The free decay of the radioactivity heats the envelope, and we follow the subsequent expansion as described above. The outer zones are accelerated quickly by the heating of the abundant shorter lived nuclei ^{14}O and ^{15}O over the first few hundred seconds. By the time 500 s have passed, several of the outermost zones have reached escape velocity. Beyond this time these zones are accelerated only slightly by further decay and the release of heat contained in the inner zones. The shells somewhat deeper are accelerated more gradually until they reach escape velocity at larger radii. In total, 4×10^{29} g (16%) of the envelope is ejected with a kinetic energy of 1.7×10^{45} ergs. The outermost zone reaches a velocity of 2700 km s^{-1}. This should be compared with model 7 of SST, which ejects 13% of the envelope with velocities ranging up to 2400 km s^{-1}. Our light curve is in reasonable agreement with theirs, although ours reaches a higher luminosity and declines faster. Our model agrees well enough with the more accurate one for estimating the gamma-ray emission.

We plot the emerging flux of photons in the annihilation line at a distance of 1 kpc, from each radioactive nucleus, in Figure 1, and the total flux in Figure 2, both as a function of time. These take into account the mode of annihilation and the scattering in the atmosphere. It appears that the amount of material exposed is too small for the shortest lived nuclei to provide an observable flux of gamma rays over their short lifetimes even for novae as close as 1 kpc. We expect about equal numbers of 2.31 MeV photons and annihilation photons from ^{14}O, because there are half as many nuclear gamma rays emitted but the Compton scattering cross section is about half of what it is at 0.511 MeV. Still, a nova would have to be much closer than 1 kpc for the 2.31 MeV flux to be observable over the first few hundred seconds, for such an abundance of ^{14}O. The nuclear decay photons from ^{34m}Cl escape in smaller fluxes but over longer times, so that the integrated flux is similar to that at 2.31 MeV. Unless the abundance of this nucleus were much higher, which is unlikely, it would not be detectable even in very close novae. We will discuss further what fluxes could possibly be detectable to present-day instruments. The situation appears somewhat more promising for the longer lived positron emitters ^{13}N and ^{18}F. Both yield fluxes at 1 kpc of over 10^{-3} photons cm^{-2} s^{-1} in the annihilation line for some time. Only positrons from ^{18}F annihilate in significant numbers via the triplet state of positronium, after $\sim 4 \times 10^4$ s. Until that time, photodissociation and ortho-para conversion by free electrons inhibit the triplet-state decay. The quantity f_2 is plotted against time in Figure 3 for this model to illustrate this point.

Model 2 is designed to simulate model 4 of STS, a 1 $M_\odot$ white dwarf with a 10^{-4} $M_\odot$ envelope. It now seems likely that dwarfs of 1 $M_\odot$ will undergo runaway after accreting envelopes of this mass or less (Starrfield, Sparks, and Truran 1986; Prialnik 1986). To achieve outburst, such envelopes must be greatly enriched with core material. Under the lesser weight, the material at the base of the envelope is less compressed and so less degenerate than matter in more massive envelopes. This particular model has carbon enhanced to 45% by mass of the envelope. This seems rather extreme, but is in line with results of the studies mentioned above which monitor the mixing of core material upward. Characteristics of this model are listed in Table 2. The peak temperature reached in the burning is $T_8 = 1.46$, at which the most significant reactions are the first two proton captures on ^{12}C. This is demonstrated by the final abundances listed in Table 2. The power for the expansion is provided mainly by the decay of ^{13}N and ^{14}O, whose initial abundances are 23% and 12% by mass, respectively. We begin

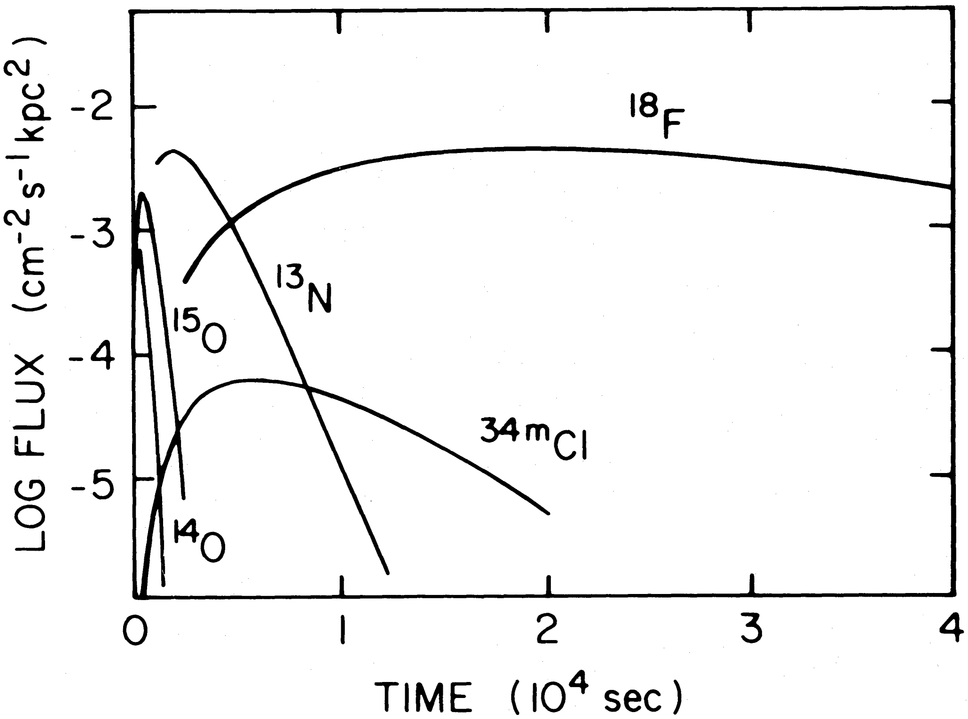

FIG. 1.—Emerging fluxes of annihilation line photons from positrons emitted by each unstable nucleus, versus time, for model 1

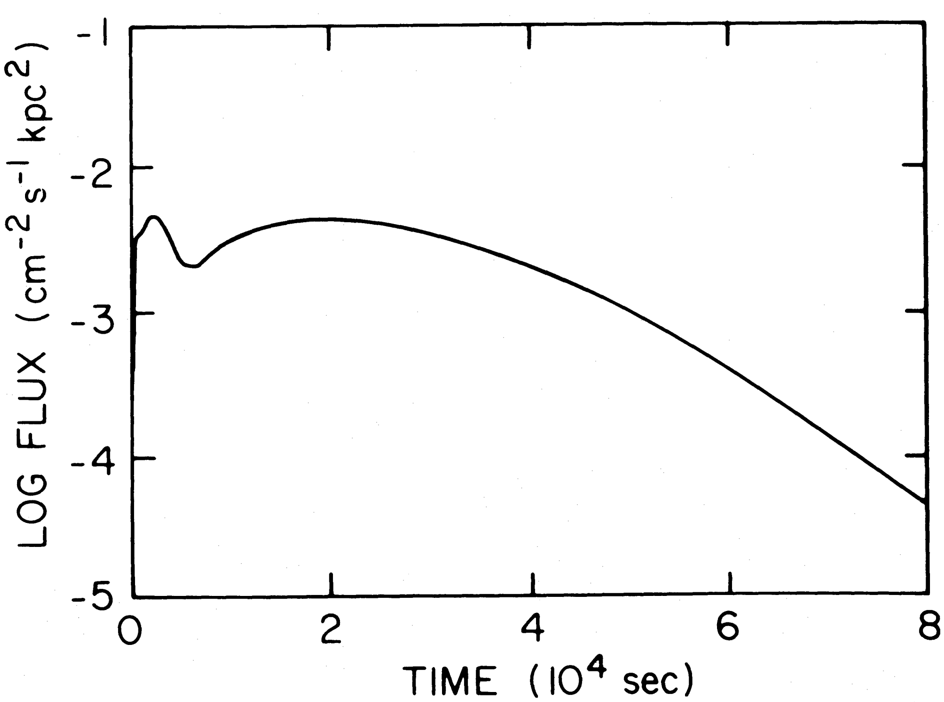

FIG. 2.—Total emerging flux of annihilation line photons versus time for model 1

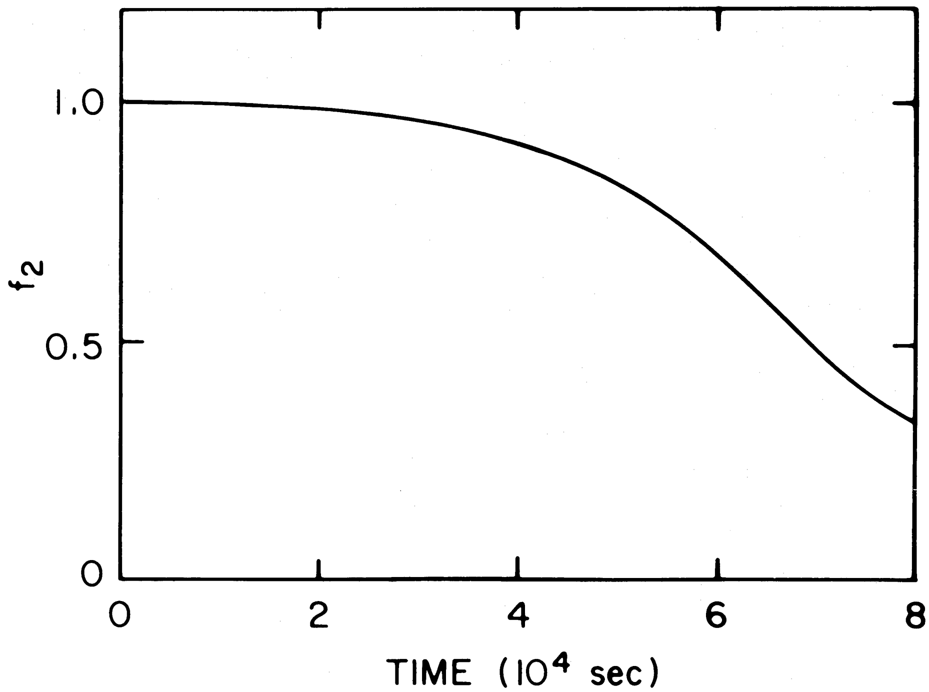

FIG. 3.—Fraction of positronium-forming positrons which yield annihilation line photons, versus time, for model 1

with the temperature at the base of the envelope equal to the peak temperature achieved in the model of STS and the outer radius appropriate to the same time (1.1×10^9 cm). A polytrope in this configuration contains 1.4×10^{46} ergs more than one with the initial conditions of STS [radius = 7.8×10^8 cm, T_8(base) = 0.1]. Producing the above concentrations of ^{13}N and ^{14}O generates 1.7×10^{46} ergs after neutrino losses. We add a heat source with an exponentially decreasing time dependence which produces 5×10^{45} ergs in the bottom zone to account for this additional energy and other reactions on ^{16}O, ^{15}N, ^{20}Ne, and so on. The positron emitters contain 1.2×10^{46} ergs in this model.

No shocks are generated in this model (STS), so the expansion as we follow it begins at a smaller radius. The high power provided by the ^{14}O decay lifts the outer envelope out of the gravitational potential, although rather slowly. After some 500 s during which the expansion proceeds at low velocity, the continued heating at larger radii by the large abundance of ^{13}N increases the velocity of expansion significantly. This leads to a rather large velocity gradient in the outer zones and produces an emerging luminosity which reaches nearly 10^{40} ergs s^{-1} in this model. The velocity of the outermost zone reaches 3400 km s^{-1}, and 6×10^{28} g are ejected. This is 30% of the envelope mass, only slightly less than the mass ejected by the more complete model of STS, and it moves only slightly faster. Again, it is not so important that the results are the same; what matters is that our simulation offers a reasonable description of the conditions obtained in a nova with these initial characteristics.

We plot the resulting annihilation line flux at a distance of 1 kpc, from each nucleus, in Figure 4, and the total annihilation line flux in Figure 5, both as functions of time. The small area of the surface at early times prevents significant escape of gamma rays, both annihilation and nuclear photons, from the shorter-lived emitters. However, the high expansion velocity leads to increased escape of photons from positrons emitted by ^{13}N and ^{18}F, with those from the former also enhanced because of its large initial abundance. The line flux from annihilation of ^{13}N positrons approaches 0.1 photons cm^{-2} s^{-1} at 1 kpc and remains above 10^{-2} photons cm^{-2} s^{-1} for some 2 hours. From ^{18}F, the flux remains above 10^{-3} photons cm^{-2} s^{-1} for over 10 hours. Orthopositronium decay is inhibited until after 2×10^4 s, when the densities of ionizing photons and free electrons are too low to destroy or convert the triplet state before it annihilates.

Perhaps the most crucial assumption in this problem is the distribution of the positron emitters at the beginning of the evolution. Ideally one would like to calculate the evolution including proper treatment of the nuclear reactions, convection, and the dynamics in a self-consistent fashion, but this is not feasible here. We assume that the positron emitters are completely mixed throughout the envelope, but it is an important question whether convection can carry positron emitters produced deep within the envelope to within a few gamma-ray mean free paths of the surface. We offer no detailed calculations to answer this question, but it seems reasonable that some of the products of the burning would be quickly carried to the surface. The tremendous temperature gradient when the peak temperature is reached in the shell source (appreciable expansion has not yet occurred) produces high convective velocities ($>10^7$ cm s^{-1}) in the rather thin (a few hundred kilometers) envelope, which is convective throughout (with convective time scales of 10 to 100 s) for a time up to and including that when the peak temperature is reached (SST; STS; Prialnik 1986). Also, the very presence of the positron emitters as a local heat source should further enhance convec-

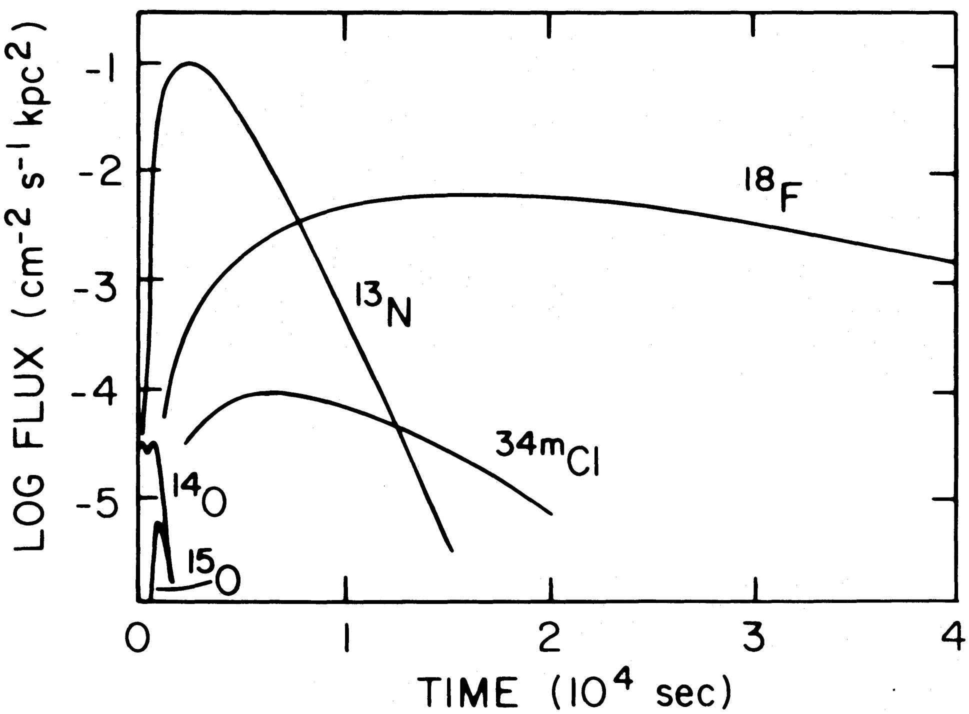

FIG. 4.—Emerging fluxes of annihilation line photons from positrons emitted by each unstable nucleus, versus time, for model 2

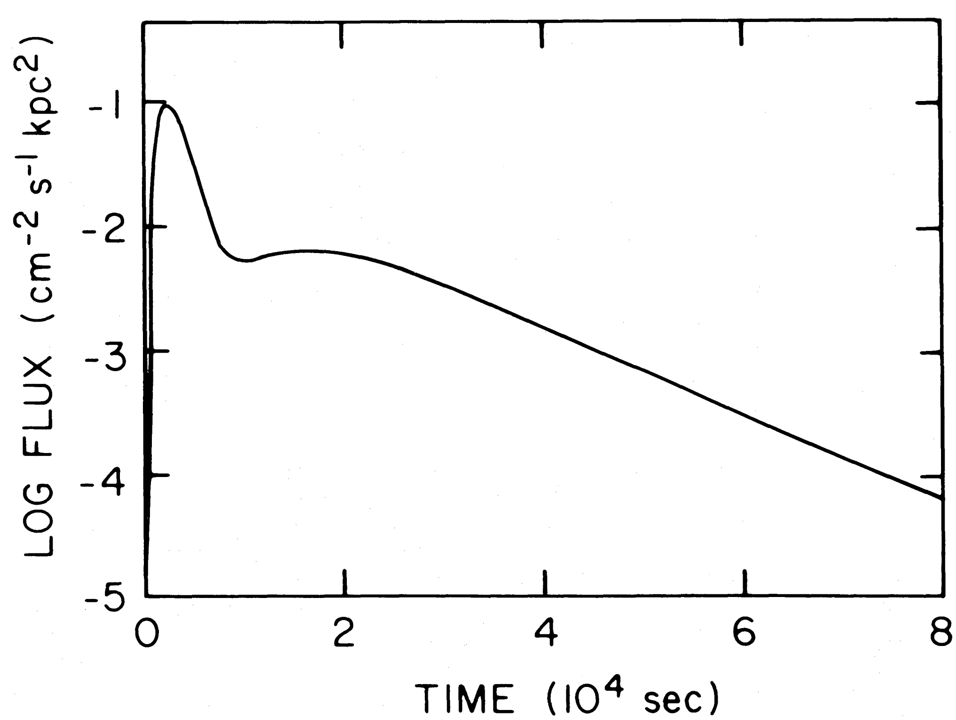

FIG. 5.—Total emerging flux of annihilation line photons versus time for model 2

tion in the outer envelope. If convection were to stop short of the surface, the heating by the radioactivity carried to the end of the convective region would further increase the temperature gradient across the convective boundary, resulting in the mixing of the radioactivity outward. Also, the observations of significantly super-Eddington luminosities in fast novae (Truran 1982) might require a heat source in proximity to the optically thin regions. In the picture of novae we have adopted, this source could be the radioactive nuclei mixed outward. If they are not mixed to the surface, the gamma rays from annihilation and nuclear decay will not be observable.

Implicit in our models and assumptions is the idea that the positron emitters provide a significant source of energy in the nova outburst. If this is true, then where this energy is produced can significantly affect the characteristics of the outburst. We attempt to justify our assumptions in a limited sense as to the distribution of radioactivity by monitoring the differences resulting from other distributions, in models otherwise identical to model 1. In one model, all the radioactivity is placed in the bottom zone, the total energy being conserved. In the resulting evolution most of the envelope is raised to a great height above the core, but only about 2% of the mass of the envelope is actually ejected in the early phase. More material should be ejected subsequently by radiation pressure, but we do not follow the evolution long enough to observe this. The luminosity emerging is significantly reduced below that of model 1. A nova-like outburst is still achieved, but its characteristics are significantly less similar to fast nova outbursts than is our model 1 (and less like the detailed model of SST on which both are based). In another variation of model 1, we remove the radioactivity from the outermost zone and redistribute it throughout the rest of the envelope. The result is an evolution similar to that of model 1 except regarding the last zone and the emerging luminosity. This zone acts as a cap on the outburst, traveling with essentially the velocity of the zone just interior to it and reducing the emerging luminosity dramatically. In fact, the luminosity never becomes super-Eddington in this model. We cannot demonstrate in detail what the mechanism of fast nova outbursts is, but given this type of model for novae, the observed characteristics of fast novae are better approximated when the unstable nuclei are mixed throughout the envelope and into the surface layers.

We further assess the effects of our assumed distributions by varying the distribution of the radioactivity in other calculations. For both models 1 and 2 we also compute companion models which are identical except that the positron emitters are initially distributed exponentially in radius, in effect allowing for free decay in the time it takes them to be convected outward from the base where they are produced. The total numbers are the same as in the uniform distribution models. The results of these models are reductions in the emerging fluxes of gamma rays due to the lower abundances in the thin regions and the reduced heating in the outer zones which produces slower expansion. For reasonable time delays between production and appearance at the surface of the positron emitters, the fluxes from ^{13}N and ^{18}F are reduced by a factor of 2 for a modified model 1. For model 2, the flux from ^{13}N is reduced by a factor of 4, while that from ^{18}F is reduced by 70%, compared with the corresponding model with uniform abundances throughout. The emerging fluxes from the shorter lived emitters are reduced even further because of the much slower early expansion. See Leising (1986) for further details of these models and results.

VII. PROSPECTS FOR DETECTION

We discuss the potential for observing these fluxes in terms of the gamma-ray spectrometer on the *Solar Maximum Mission* (*SMM* GRS) and the Oriented Scintillation Spectrometer Experiment on the Gamma-Ray Observatory (GRO OSSE). The sensitivities of the detectors depend on the time over which the fluxes are integrated. In the simple case that both background and source are constant in time, the detector sensitivity limit essentially decreases with time as $t^{-1/2}$. We employ this approximation to compare the predicted fluxes with detectable limits. OSSE on GRO is expected to reach a sensitivity of 2×10^{-5} photons cm^{-2} s^{-1} for 10^6 s integrations (Kurfess *et al.* 1983), so we estimate that it should reach 6×10^{-4} photons cm^{-2} s^{-1} (or a fluence of 0.6 photons cm^{-2}) in 10^3 s integrations, for example. GRS on *SMM* is sensitive to a flux of 3×10^{-3} photons cm^{-2} s^{-1} (a fluence of 3.0 photons cm^{-2}) at 0.511 MeV in a 10^3 s integration, at least at times of low background. In Table 3 we list the integrals over the relevant times of the annihilation fluxes from each nucleus, for each model. We also list the fluences to which OSSE and *SMM* are sensitive over the same integration times, assuming that they scale as the square root of the time. It appears that a nova like model 1 could be detected via annihilation photons from ^{13}N by either detector if it occurs within a kiloparsec or so, while a nova very rich in ^{13}N like model 2 could perhaps be detected up to the distance of the Galactic center by OSSE. Either model could be detectable in photons produced by ^{18}F decay, up to distances of 5 kpc or so, if occurring in the OSSE field of view. *SMM* could detect those photons from novae perhaps half that distant. The likelihood of a detection by OSSE is

TABLE 3

INTEGRATED ANNIHILATION LINE FLUXES

Isotope	Integration Time (s)	Calculated Fluences (cm^{-2})[a]		Sensitivity Limits (cm^{-2})	
		Model 1	Model 2	OSSE	*SMM*
^{13}N	3000	14.4	328	1.1	5.2
^{14}O	200	0.3	0.04	0.3	1.3
^{15}O	400	1.4	0.005	0.4	1.9
^{18}F	6×10^4	146	173	4.9	23.2
^{34m}Cl	10^4	0.7	1.0	2.0	9.5
Total	6×10^4	163	502	...	...

[a] At distance of 1 kpc.

reduced by its field of view (3°.5 × 11°). The *SMM* GRS, on the other hand, has a field of view of 120° FWHM, which greatly increases the chance of detection of a nearby nova.

The spectrum of the emitted gamma rays is dominated by the annihilation line, but also contains the continuum from orthopositronium annihilation and Compton-scattered photons of both line and continuum origin. The spectrum will evolve in time, but what is relevant for detection is the spectrum integrated over some time. Figure 6 shows the spectrum of model 1 integrated over the entire 8×10^4 s of its evolution which we follow. The nuclear decay lines do not appear to be readily detectable. The total integrated spectrum of model 2 is very similar. Although at late times the continuum is stronger relative to the line than for model 1, the intense early emission of line photons and scattered continuum from ^{13}N hide the orthopositronium continuum in the total integrated spectrum. Figure 6 displays photon numbers in 5 keV intervals and does not present line profiles. Since an observer would see only the approaching ejecta, the line would be blueshifted. A thin, spherically expanding shell yields a flat-topped line profile, but in the thick ejecta there is greater self-shielding at the limb of the shell (where the line-of-sight velocity is zero) per unit depth in mass. Thus what results is a profile which is substantial from 511 to 516 keV (assuming 3000 km s^{-1} expansion) but rises over that range. This profile will be further broadened by thermal motions, by about 3 keV initially, decreasing to 1 keV after a few hours.

VIII. POSITRON ESCAPE

We calculate the range for positrons of the average energy emitted by each nucleus of interest, and assume that one-quarter of the positrons emitted within a depth from the surface equal to the range actually escape. This yields an estimate of the rate of escape of positrons from the envelope. As with the annihilation photons, ^{13}N and ^{18}F are the major contributors. Integrated over the time which we follow the evolution, the total numbers of positrons which escape are 2×10^{43} and 2×10^{44} for models 1 and 2, respectively. Even given the uncertainties in this calculation, these totals are insignificant compared with other proposed sources of the Galactic positron annihilation radiation—for example, Type I supernovae (e.g., Colgate 1983) or even ^{22}Na and ^{26}Al produced in novae. If 10^{-8} $M_\odot$ of each is produced in a nova, 10^{48} positrons result, most of which escape because of the delay between outburst and the radioactive decays.

IX. CONCLUSIONS

It appears that positron-electron pair annihilation radiation could be detectable during the early stages of a nova outburst if the nova is relatively near, the production of ^{13}N and/or ^{18}F is near the upper limits of what might reasonably be expected, and the products of the thermonuclear runaway which are produced relatively deep within the envelope are rapidly convected to very near the photosphere. This last provision is probably the most uncertain at present, and has not been demonstrated with detailed calculations. The observed characteristics of fast nova outbursts are, perhaps, more readily explained in terms of the standard thermonuclear runaway theory if the radioactive heat source is carried to the surface. Nevertheless, detailed calculations with self-consistent formulation of the nova dynamics, convection, and nuclear reactions are demanded, not only for the solution of the problem at hand but also for the entire question of nucleosynthesis in novae. There are many simplifications and generalizations in the cal-

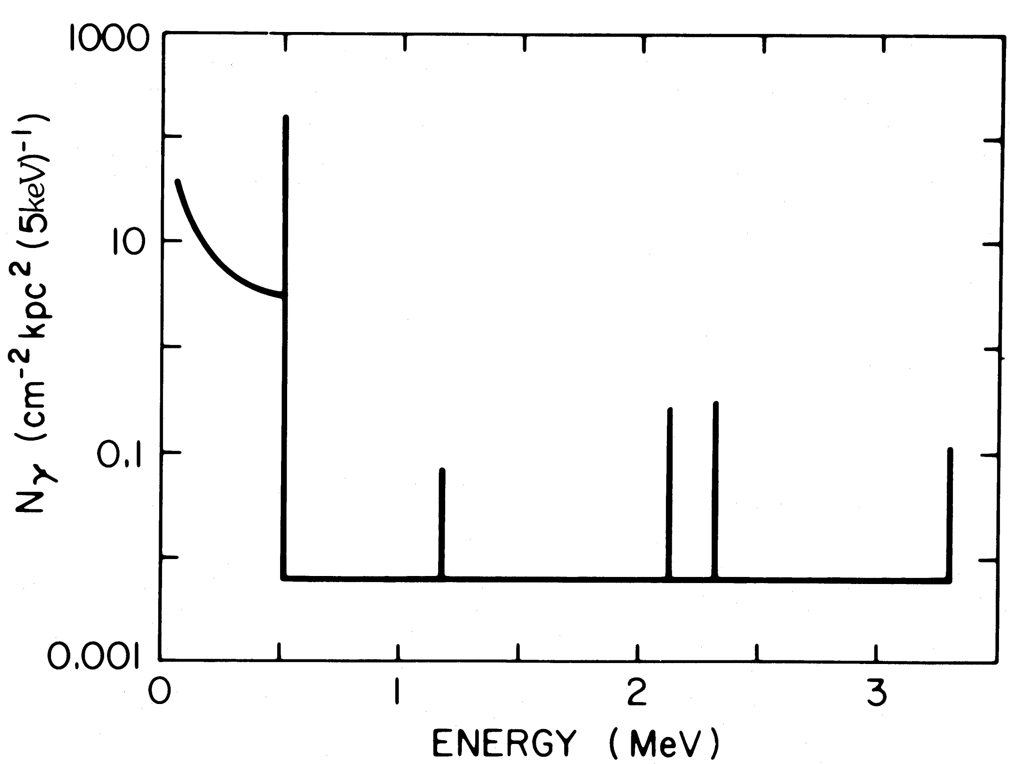

FIG. 6.—Time-integrated (over 8×10^4 s) spectrum from 50 keV to 3.3 MeV for model 1. The spectrum is plotted as photon number in 5 keV bins (line profiles are too narrow to appear on this scale).

culations described here which may affect the details of the results. For example, both the runaway and the convective processes could be highly nonspherical, so that the symmetry implicit in these calculations could be destroyed. Circumbinary material present prior to the outburst, or envelope material shock-ejected before radioactivity reaches the surface, could mask the gamma rays, at least at early times. In spite of the uncertainties and possible circumstances which could preclude significant gamma-ray escape, the results obtained here are encouraging enough that it seems worthwhile to search for gamma-ray signatures of novae. Any such detection could teach us much about the nature of nova outbursts, not only confirming existing theoretical ideas but also illuminating the conditions of the early outburst which we might not be able to monitor in any other way. This would be especially true if nuclear decay lines were also detected, but that prospect seems unlikely for the short-lived nuclei discussed here. Also, this is far from an ideal observing situation. Systematics inherent in any gamma-ray observations make detection of variability on time scales of hours most difficult. The fact that 0.511 MeV gamma rays are produced in the atmosphere, in spacecraft and detectors, and in other celestial sources render observations of annihilation photons especially difficult. As is often the case in gamma-ray astronomy, the expected intensities and the sensitivities of the instruments are comparable, so that upper limits will not likely be very instructive. A detection, a direct real-time observation of products of nuclear reactions which could illuminate nova dynamics, would be most exciting.

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