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ON THE RELATIONSHIP OF THE NUCLEAR LUMINOSITY TO THE OPTICAL MAXIMA OF FAST CLASSICAL NOVAE

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Abstract

Observations of fast classical novae indicate the existence of a large and serious disagreement with theory, regarding the maximum luminosities achieved by these systems. Fast novae in our Galaxy, and those in M-31 and the LMC (for which distances are particularly well determined), reach absolute visual magnitudes as bright as -8.5 and can remain brighter than -7 for several days. This behavior has not been successfully reproduced by any self-consistent, time-dependent numerical simulation. We demonstrate that existing numerical models are energetically capable of powering such observed emission for the requisite timescale, and argue that the discrepancy arises due to the fact that the physics describing the exchange of energy and momentum between the material and radiation has been oversimplified in the hydrodynamical studies published to date. Efforts currently underway to remedy this situation are described.

Subject headings: stars: novae

1 INTRODUCTION

The purpose of this paper is to call attention to an area of theoretical nova research which has presented a long-standing problem to workers in the field, namely the modeling of the outburst maximum of the fastest and brightest classical novae (hereafter: CNe). There exists a large and compelling body of data for novae in our galaxy (Payne-Gaposchkin 1957; de Vaucouleurs 1978), M-31 (Arp 1956; Ciardullo, Shafter, Ford, Neill, Shara, & Tomaney 1990), and the Large Magellanic Cloud (Starrfield, Hauschildt, Shore, Sonneborn, Gonzales-Riestra, & Sparks 1992), which indicates that the fastest CNe achieve maximum absolute visual magnitudes of -8.5 or brighter, and remain brighter than M_v = -7 for timescales of several days (typically three to five). This behavior has, to date, defied all theoretical attempts at numerical reproduction. The association of magnitude -7.1 with the Eddington limit for a stellar mass of approximately 1.4 $M_\odot$, and the expectation that fast classical novae will occur predominantly on white dwarfs in the range $1.2 \leq M_{\rm wd}/M_\odot \leq 1.3$ has led to use of the term "super-Eddington phase" (Truran 1982; Hayes, Truran, Livio, & Shankar 1990) in conjunction with discussions of the outburst maximum of fast CNe . Further attention to the super-Eddington character of fast novae was drawn by the observation (Truran 1982) that the dividing line separating super- and sub-Eddington novae was coincident with that which separates the "fast" and "slow" novae; i.e. all of the fast novae classified as "fast" and "very fast" by Payne-Gaposchkin (1957) exhibited peak luminosities above the Eddington limit for even a Chandrasekhar mass white dwarf, whereas none of the slower novae showed this behavior. In spite of the apparent connection between the Eddington limit and speed class, however, use of the term "super-Eddington" in the context of nova evolution is somewhat dangerous, for two reasons:

(1) The Eddington limit is only defined in media which are hydrostatic and purely radiative at the outset. Time-dependent models of nova outbursts violate both of these conditions well before reaching their maximum luminosities, and thus much of the folklore concerning the distribution of energy between radiation and material flow for input luminosities above $L_{\rm edd}$ is inapplicable. An under-appreciated fact of radiation hydrodynamics (Castor 1986) is that in moving media, *sustained*, highly super-Eddington luminosities are achievable *provided that sufficient input energy exists.*

(2) The formal expression for the Eddington limit,

$$L_{\rm edd} = \frac{4\pi GcM}{\kappa}, \qquad (1)$$

is a function of stellar mass and opacity. Assuming that the opacity is pure electron scattering, and further assuming that the material is fully ionized hydrogen, one may transform (1) into

$$L_{\rm edd} = 3.8 \times 10^4 L_\odot \left(\frac{M}{M_\odot}\right). \qquad (2)$$

Use of this expression yields the advertised magnitude value given above. The dangerous aspect of this is that one may redefine the extent to which a model sequence exhibits super-Eddington luminosities, and the length of time over which such luminosities are realized, by referring at various points in the envelope to local values of the Eddington limit, defined in terms of the actual opacity at that point, rather than the canonical electron-scattering value. While this is certainly sensible physically, it entirely ignores the nature of the discrepancy between theory and observations mentioned above: *no* self-consistent, time-dependent nova simulation has achieved a maximum visual magnitude of -8.5 and stayed above -7 for 3 days, whereas a large number of real nova systems have done *precisely* that. This basic statement is true *irrespective* of the exact definition of the Eddington limit. Because of these potential sources of confusion, this paper will downplay the use of the Eddington limit as the quantity of interest, and will instead simply focus on that portion of the outburst over which a nova system (real or simulated) maintains a luminosity brighter than magnitude -7.

2 THEORETICAL ISSUES

2.1 The Energy Budget

The essence of the difficulty in modeling the outburst maximum of fast CNe is summarized by Hayes, Truran, Livio, & Shankar (1990). They find that there exists a minimum set of conditions which must be met for a nova to attain any degree of super-Eddington emission for any length of time. However, the models presented therein and in a subsequent series of unpublished calculations (Truran, Hayes, Livio, & Shankar 1991) were unable to produce *bolometric*

luminosities which remained above magnitude -7 for more than a few hours and, furthermore, were unable to generate *visual* magnitudes brighter than this value for *any* length of time. The minimum conditions needed for a numerical simulation to achieve any degree of super-Eddington output are identical to those long recognized as necessary for rapid lightcurve evolution and substantial mass ejection (for recent reviews, see Truran 1982; Starrfield 1989; Truran 1990): large CNO enhancements in the accreted envelope, significant energy release from positron-unstable nuclei produced by the CNO-cycle reactions, and a level of convective mixing sufficient to distribute these nuclei throughout the envelope on short timescales.

In spite of the success in identifying the key roles played by these factors in a nova outburst, the difficulty in producing peak luminosities of the proper magnitude has held fast. Considerable progress in understanding the source of this diffculty can be made, however, by obtaining answers to the following two questions: (1) Does the existing theoretical picture of a nova outburst as a thermonuclear runaway event allow, even in principle, for the attainment of such high outburst luminosities? Put another way: do existing numerical models possess enough energy to power a three-day super-Eddington event? (2) If the answer to (1) is "yes," then what physical processes are being ignored, or treated incorrectly, in our efforts to simulate fast CNe numerically?

To answer the first question, we need simply to look at the total energy generated by the nova model as a function of time; i.e. we must examine the evolution of the nuclear luminosity. The numerical work presented here was performed with HYDRA, a one dimensional, Lagrangian, implicit radiation hydrodynamics code which is a highly modified version of the code developed by Kutter & Sparks (1972), and subsequently used by Starrfield, Sparks, & Truran (1974a,b; 1980, 1985, 1986) in a variety of nova studies. Details of the similarities and differences between HYDRA and its predecessor may be found in Hayes (1993a,b). Figure 1 shows the total nuclear energy generated as a function of time for a model sequence computed as part of the thesis work of Hayes (1993a). This nova simulation was characterized by a white dwarf of mass 1.25 $M_\odot$, and an initial luminosity of 5×10^{-3} $L_\odot$. An accretion rate of 10^{-9} $M_\odot$ per year was chosen, which resulted in the onset of a thermonuclear runaway after an accretion phase of 7500 years' duration. The composition of the accreted envelope had a total CNO abundance (by mass) of 0.6, consistent with both observational and theoretical expectations of the compositions of the envelopes of fast CNe. In the figure, t=0 was chosen to be the time at which the nova became bolometrically brighter than magnitude +7, at which time the subsequent evolution of the bolometric lightcurve became extremely rapid. What is immediately apparent from this figure is the length of time required for the nuclear energy generation rate to drop below our reference magnitude of -7. We see that this model sequence achieved an integrated energy generation rate that is not only super-Eddington at maximum, but remains brighter (in terms of total energy output) than mag. = -7 for nearly five days, which is precisely the desired timescale. The answer to our first theoretical question, at least for the model displayed in Figure 1, is a resounding *yes*.

The model sequence displayed above was one of nine such simulations performed by Hayes (1993a). The results of that work showed that the nuclear behavior shown above is not unique to the model sequence decribed here, but is in fact a common feature to these simulations. Since the purpose of this paper is to call attention to a new aspect of nova modeling in a concise fashion, the results of the other simulations will not be given here, but will instead appear in a future paper. The results of the models presented here and in Hayes (1993a) indicate that these simulations are energetically capable of powering optical lightcurves with the proper maximum luminosities and decline timescales, provided that the rest of the physics is done correctly. Additionally, one may easily show that the nuclear evolution timescale shown in Figure 1 is understandable on very basic physical arguments. To see this, let us consider a white dwarf of mass $M_{\rm wd}$ which has an accreted envelope of mass $M_{\rm env}$. Suppose a steady energy input is incident upon the base of the envelope at a rate $L_{\rm nuc}$. The timescale for expansion of the envelope against gravity is then given by the Kelvin-Helmholtz timescale:

$$\tau_{\rm KH} = \frac{G M_{\rm wd} M_{\rm env}}{R_{\rm wd} L_{\rm nuc}}. \qquad (3)$$

The 1.25-$M_\odot$ model displayed in Figure 1 had an accreted envelope of 7.5×10^{-6} $M_\odot$ at the beginning of the runaway and a radius of 3.4×10^8 cm at the core-envelope interface. A total of 6.2×10^{45} ergs of nuclear energy were deposited into the envelope during the first 4.1×10^5 seconds of post-runaway evolution,

which translates into an average nuclear luminosity of 1.5×10^{40} ergs per second over that time period. Use of these numbers in equation (3) leads to a value of roughly 5.5 days for τ_{KH}, which is in excellent agreement with the timescale for the nuclear luminosity to return to its plateau value, as in Figure 1. We thus see that the evolutionary behavior of the nuclear energy generation rate is a natural consequence of the associated Kelvin-Helmholtz evolution time of the accreted envelope.

The Kelvin-Helmholtz timescale provides additional support for the significance of CNO enhancements, positron decay energy, and convection as mentioned earlier. Consider the sequence of events which must transpire during this time frame in a fast nova outburst. A fast classical nova evolves from its very low pre-outburst luminosity through its highly super-Eddington peak and back down to sub-Eddington values in a total time of a few times 10^5 seconds. Clearly, then, the accreted envelope must undergo TNR-induced expansion on a timescale much *shorter* than 10^5 seconds. Physically, this is equivalent to demanding mechanisms which act to unbind the envelope and initiate efficient energy transport on short timescales. The combined action of convection and energy deposition from β-unstable nuclei is the ideal mechanism for accomplishing rapid envelope envolution, for it is these two processes which allow significant energy deposition in the surface regions of the envelope. Were it not for the deposition of the β-decay energy *throughout* the accreted envelope, rather than purely at the envelope base, the evolution of all nova lightcurves would be severely constrained by the Kelvin-Helmholtz timescale and the even longer radiation diffusion timescale, and the observed rapid evolution of fast CNe would not be possible.

2.2 Energy Partitioning

Having verified that the standard thermonuclear runaway model of a nova outburst is energetically capable of powering the optical luminosities observed in actual nova systems, we must now examine our second question: what physical processes remain to be incorporated into a nova simulation which would allow the observed luminosities to be reproduced? Progress toward answering this question can be made simply by considering the issue from a different angle: given that our nova models can generate energy in sufficient quantities, where is the energy going? The alert reader will likely not be surprised to see that the answer is mass loss. To appreciate the demands upon the total energy budget made by the material outflow, consider the following: at maximum light, a typical fast nova processes a peak luminosity in excess of 10^5 $L_\odot$ and an effective temperature in the neighborhood of 10^4 K. The implied photospheric radius is then on the order of 10^{13} cm. Given that optical maximum is reached on a timescale of 10^5 seconds, the expansion velocities must be on the order of 10^8 cm s^{-1}. We may use this knowledge to evaluate the mass outflow rate at the photospheric radius, if we have an estimate of the mass density at that radius. Such an estimate may be obtained in two different ways. First, one may assume that we have an ionized, extended atmosphere, such that the opacity is dominated by electron scattering, and that the mean free path at the photospheric depth is on the order of the photospheric radius itself. Alternatively, one may consult the results of the numerical runs discussed earlier. Both methods yield similar results, namely that a representative value of density at the photosphere, during outburst maximum, is approximately 10^{-13} g cm^{-3}. Use of this number gives a value of roughly 10^{22} grams per second for the mass outflow rate. Since the material is initially arranged in a very thin shell at the white dwarf surface, one may translate the mass loss rate into a mechanical luminosity as follows:

$$L_{\dot{m}} = \frac{GM_{\rm wd}\dot{m}}{R_{\rm wd}}. \qquad (4)$$

Evaluation of equation (4) for a white dwarf with a mass of 1.25 $M_\odot$ and a surface radius of 3.4×10^8 cm yields a value of about 10^6 $L_\odot$ for $L_{\dot{m}}$. The 1.25 $M_\odot$, high-CNO model sequence presented here did, in fact, achieve and maintain a mechanical luminosity of this magnitude for the first day and a half of its post-TNR evolution. The implication, therefore, is that a transferal of only ten percent of the mechanical power into optical light would produce a lightcurve far more consistent with observations than what is currently achieved. This fact is vividly demonstrated by Figure 2, which was obtained by translating the photospheric mass flux into a mechanical luminosity, multiplying that value by 0.1, and plotting the result vs. time on a magnitude scale. Thus Figure 2 shows, for our 1.25 $M_\odot$, CNO-enriched model sequence, the bolometric lightcurve which would have resulted by converting a mere ten percent of the mechanical power into luminous output. This is just the type of lightcurve we seek.

What are we to conclude from this exercise? We seek to identify physical processes which influence the emergent radiation field; the clear implication of this discussion is that the mechanisms governing the exchange of energy and momentum between matter and radiation have not been treated adequately by the standard hydrodynamic prescription. The preceding exercise indicates that a relatively minor reduction in the mechanical power output could have a potentially enormous effect upon the emergent luminosity. A potential source of trouble with the standard hydrodynamic treatment employed in nova simulations thus far is the lack of differentiation between processes that absorb radiation, and those which scatter it. To see the possible consequences of this non-distinction, let consider the interaction between a single atom and an incident photon, and compare the relative amounts of energy and momentum transferral in the absorption and scattering cases. Suppose we have an atom in a stellar envelope moving radially outward with a velocity of v, which is overtaken and "struck" by an outward moving photon of frequency ν. In the rest frame of the atom, the photon is doppler shifted to the comoving frequency, ν', given by

$$\nu' = \nu\left(1 - \left(\frac{v}{c}\right)\right). \tag{5}$$

If the atom has a strong spectral line at ν', then the photon may scatter backwards off the atom at this comoving frequency, and thus in the lab frame will have a new frequency of

$$\nu_s = \nu\left(1 - 2\left(\frac{v}{c}\right)\right). \tag{6}$$

The consequence of this is that, while the photon transfered 100 percent of its momentum to the atom, it has lost only $100 \times (2v/c)$ percent of its energy. For an outflow velocity of 3000 km s^{-1}, which is typical in early-type stars and novae, such a photon will only lose two percent of its energy per each scattering event! By contrast, a photon which is absorbed by an atom which then de-excites collisionally will surrender *all* of its energy along with its momentum.

The implication of the preceding discussion is that the character of the emergent radiation may depend sensitively upon the physics controlling the exchange of energy and momentum between the material and the radiation field. In particular, the issue of absorption vs. scattering in the expanding, radiating fluid may play a pivotal role in meeting the relatively modest demands of the optical lightcurve upon the total energy budget. In response to this idea, work is now underway to upgrade the radiative transfer physics used in a time-dependent nova simulation. Information regarding absorption/scattering processes may be introduced into the hydrodynamic equations through use the of radiation energy conservation equation:

$$\rho\left[\frac{D}{Dt}\left(\frac{aT_R^4}{\rho}\right) + \left(\frac{aT_R^4}{3}\right)\frac{D}{Dt}\left(\frac{1}{\rho}\right)\right] = \nabla\cdot\left(\frac{4}{3}\frac{acT_R^3}{\overline{\chi}}\nabla T_R\right) + ac\left(\kappa_P T^4 - \kappa_E T_R^4\right). \tag{7}$$

In this equation, $T_{\mathcal{R}}$ is the *radiation temperature*, defined such that aT_R^4 yields the integrated radiation energy density. In general, the radiation temperature need not equal the material temperature; in circumstances where the two are unequal, the radiation is said to propagate via *nonequilibrium* or *two-temperature* (2-T) diffusion. The symbols κ_P and κ_E refer to the Planck and absorption mean opacities, respectively; the other symbols have their usual meanings. The first term on the left-hand side of equation (7) represents the total change of the radiation energy with time; the second term is the PdV term describing the rate of work done by the radiation field on its surroundings. The first term on the right-hand side of equation (7) is the net gain or loss of radiant energy due to gradients in the total luminosity. The second term on the right-hand side is the key ingredient to our discussion here, for it describes the contribution to the radiation energy balance from the material via absorption and emission processes. Thus not only does this term describe the processes which will determine the degree of thermal coupling between the material and the radiation, but also it distinguishes the *absorptive* opacity from the total opacity (represented here by $\overline{\chi}$), which in general is the sum of absorptive and *scattering* contributions.

A major part of the thesis work of Hayes (1993a) was to incorporate this equation into HYDRA, thereby allowing it to solve the 1-D equations of radiation hydrodynamics, in the comoving frame, in either the 1-T or 2-T diffusion approximation. As of this writing, however, the radiation energy equation in the 2-T algorithm has not yet been written to include the absorption mean opacities explicitly as shown in equation (7). What has been done instead is to replace

both κ_P and κ_E with an opacity of the form $A \cdot \chi_R$, where χ_R is the Rosseland mean opacity, and A is a constant less than or equal to 1.0. This approach has two attractive features: (1) it does not require access to special tables of opacity beyond the standard Rosseland means, and (2) it is simpler to implement and thus much faster to debug; this is of special importance when taking a new (or drastically revised) code through its initial "shakedown" phase.

This approach also has two very severe drawbacks from the standpoint of stellar modeling, however. These are: (1) the Rosseland mean guarantees correct momentum and energy transport in the stellar interior where the material is very optically thick, but breaks down in the optically thin surface regions (Mihalas 1978; Mihalas & Mihalas 1984) and (2) in a CNO-enriched nova envelope, the A coefficient cannot possibly be described by a constant. From the moment that the β-decay energy breaks through the envelope surface to the point where the luminosity has reached its maximum value, the temperature near the envelope surface evolves from roughly 10^7 K down to a few times 10^4 K. If the material were pure hydrogen, this would be of little consequence since hydrogen is essentially fully ionized over that temperature range. For a mixture which is heavily enriched in CNO elements, however, that statement is not even remotely correct. This means that a CNO-rich nova envelope will evolve right through the heart of the temperature domain encompassing CNO excitation and ionization/recombination. In such a situation it is absolutely crucial to know the relative ionization balance in the envelope, for this will determine the relative contributions from absorption and scattering to the momentum and energy balance in the radiating fluid. Thus the implementation of the radiation energy equation currently present in HYDRA effectively ignores all of the important physics espoused in this paper. Given the manifest importance of including these processes correctly, work is proceeding to fully implement non-equilibrium diffusion in a physically sensible manner; the results from such efforts will be reported in a future paper.

3 SUMMARY

This paper has called attention to the fact that there exists a great discrepancy between theory and observations regarding the outburst maximum phase of fast CNe. Fast CNe, for which reliable distance determinations exist, show peak absolute visual luminosities far brighter than those currently obtainable by numerical simulations. Furthermore, these objects remain *visually* brighter than absolute magnitude -7 for times far longer than those *bolometrically* obtainable by the current numerical models. However, we have seen that the numerical models do possess the needed energy to power an optical lightcurve consistent with that observed, but the mechanisms governing the exchange of energy and momentum between the material and the radiation appear to be improperly treated in the present hydrodynamical scheme. Because of the extremely modest demands placed upon the total energy budget by the optical emission, it is essential that the process of momentum and energy exchange between the material and radiation, particularly with regard to absorption and scattering of radiation, be treated in a realistic fashion. Work is now underway to address this issue by upgrading HYDRA to explicitly treat the expanding envelope as a two-component fluid which may experience variable levels of coupling between the material and radiation, and which may evolve in an appropriate fashion when absorption and scattering process are distinguished properly.

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FIGURE CAPTIONS

Figure 1.—The nuclear luminosity (solid line) and bolometric luminosity (dashed line) vs. time for a nova model sequence with $M_{wd} = 1.25\ M_{\odot}$ and $Z_{cno} = 0.6$.

Figure 2.—An artificial bolometric lightcurve for the same model sequence shown in Figure 1. The bolometric luminosity plotted here corresponds to ten percent of the mechanical luminosity.

FIGURE 1

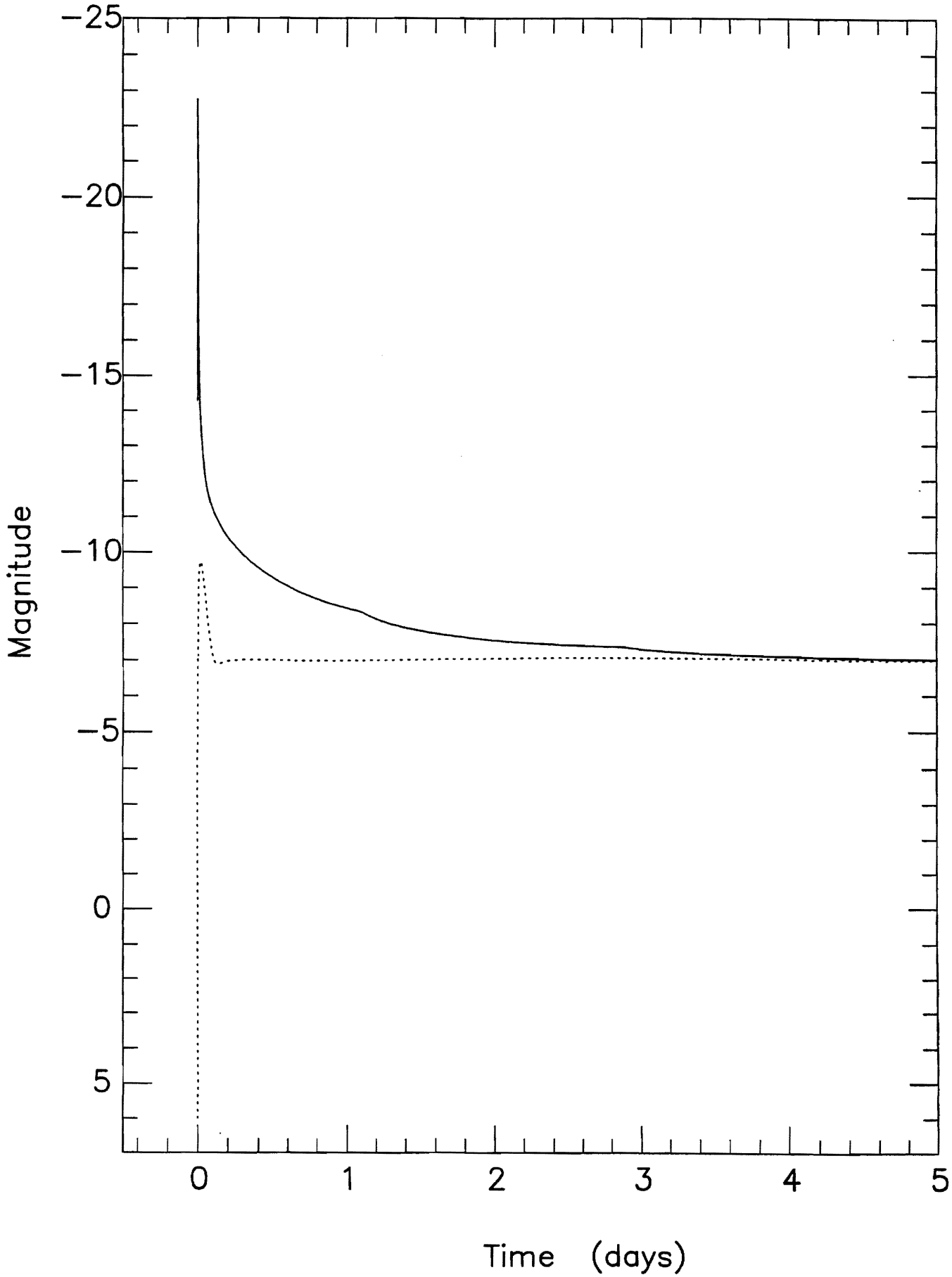
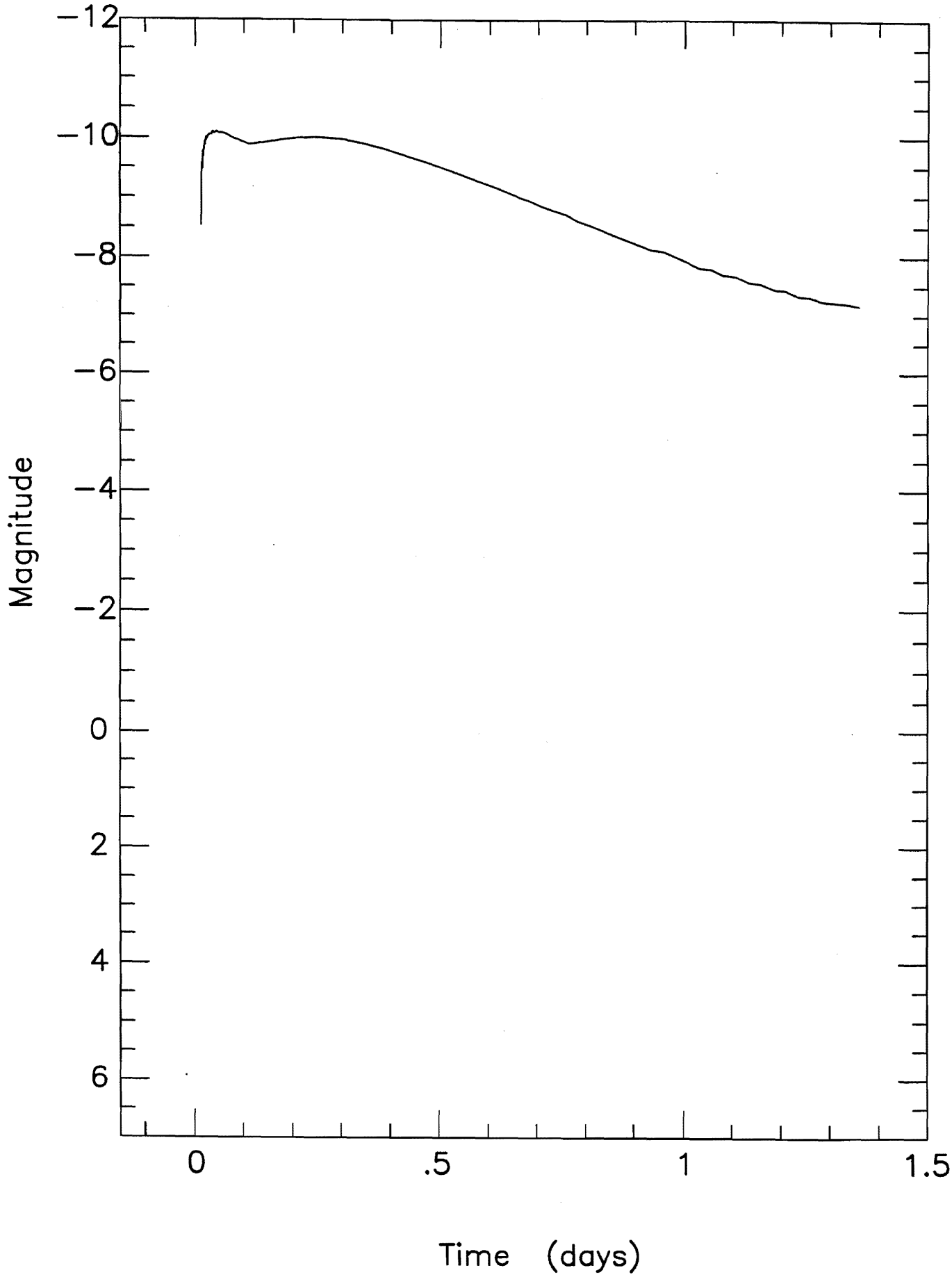
FIGURE 2