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BOUNDARY LAYERS IN CATACLYSMIC VARIABLES: THE HEAO-1 X-RAY CONSTRAINTS

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ABSTRACT

X-ray observations of novae, nova-like variables, and dwarf novae in outburst have shown them to be weaker X-ray sources than expected from models attributing the X-ray emission to a boundary layer formed between the white dwarf surface and an accretion disk. A resolution of this discrepancy is important for understanding the accretion process in cataclysmic variables. Constraints on the X-ray emission from novae can be derived from the lack of detections of novae in the HEAO-1 soft X-ray sky survey. An analysis of these constraints suggests that the discrepancy can be resolved if novae, nova-like variables, and dwarf novae in outburst have optically thick boundary layers with kT = 15-30 eV, provided the neutral hydrogen column densities of circumstellar gas are $\gtrsim 10^{20.5}$-10^{21} cm^{-2}. If so, we do not observe a strong hard X-ray flux (E > 1 keV) from these systems because an optically thick boundary layer will not be a hard X-ray source. Likewise, we do not observe a strong soft X-ray flux (E < 0.5 keV), even though it is produced in the boundary layer, because most of this flux is absorbed by circumstellar gas. The importance of the photoelectric absorption of soft X-rays by circumstellar gas may have been underestimated in previous work. The weak hard X-ray fluxes commonly observed from novae, nova-like variables, and dwarf novae in outburst may be produced in an accretion disk corona.

Subject headings: stars: accretion - stars: dwarf novae - stars: novae - X-rays: binaries

I. INTRODUCTION

Accretion models for cataclysmic variables (CVs) predict the formation of a boundary layer at the interface between the white dwarf surface and an accretion disk (Lynden-Bell and Pringle 1974). The boundary layer is expected to radiate an EUV/soft X-ray flux if it is optically thick (Pringle 1977) or a hard X-ray flux if it is optically thin (Pringle and Savonije 1979; Tylenda 1981). Approximately half the gravitational energy released by accretion should be released by dissipation of rotational energy in the boundary layer so that boundary layer luminosities greater than 10^{33} ergs s^{-1} are expected. X-ray observations of CVs, however, have shown most of them to be weaker X-ray sources, with X-ray luminosities less than 10^{32} ergs s^{-1} (Cordova and Mason 1983). A discrepancy between the observed low X-ray luminosities and the luminosities expected from the boundary layer has been noted, particularly for the nova subclass of CVs, by Cordova, Jensen, and Nugent (1981; hereafter CJN), Becker (1981), and Ferland et al. (1982a). It is difficult to explain the absence of a boundary layer if the standard accretion model for CVs is correct. A resolution of this discrepancy is therefore important for understanding the accretion process in CVs.

The purpose of this paper is to extend the CJN treatment of HEAO-1 constraints on the X-ray emission from novae to provide a better understanding of the boundary layers in novae. The HEAO-1 constraints are particularly useful for determining whether the boundary layers in novae are optically thick or optically thin, and for estimating the boundary layer temperatures and neutral hydrogen column densities to the boundary layer.

In §II, I summarize the predictions of the boundary layer model for the X-ray emission from novae. A comparison with the X-ray observations is made in a review of previous suggestions that a discrepancy exists between the observations and the theory. In §III, I extend the work of CJN to provide constraints on the nature of boundary layers in novae, based on the lack of detections of novae in the HEAO-1 soft X-ray survey. As a result, I will show that hard X-rays from novae are unlikely to be produced in a boundary layer. I will also provide estimates of temperatures and column densities for optically thick boundary layers in novae. In § IV, the applicability of these results to other subclasses of CVs, and their implications for the nature of boundary layers, circumstellar gas in CVs, and the hard X-ray source in CVs, are discussed.

II. THE NOVA PROBLEM

a. The Standard Model

The standard accretion model for CVs makes the following predictions.

Approximately half of the gravitational energy released by accretion will be radiated from the accretion disk. Accretion disk luminosities of $GM\dot{M}/2R$ = 8.5×10^{33} $(M/M_0)(\dot{M}/10^{-9}\ M_0\ yr^{-1})(5 \times 10^8\ cm/R)$ ergs s^{-1} are expected, where M is the mass of the white dwarf, $\dot{M}$ is the mass accretion rate onto the white dwarf, and R is the radius of the white dwarf. The accretion disk will not be hot enough to be an X-ray source (Shakura and Sunyaev 1973).

The remaining half of the energy released will be radiated from a boundary layer between the white dwarf surface and the accretion disk. The luminosity of the boundary layer should be approximately half the total accretion luminosity.

If the boundary layer is optically thick, it should radiate as a 15-30 eV blackbody from an annulus with inner radius R and outer radius R+h, where h(<<R) is the semi-thickness of the inner accretion disk (Pringle 1977). Half of this radiation will be occulted by the white dwarf. The observable luminosity from this blackbody component should therefore be approximately one

quarter of the total accretion luminosity. A fraction of this radiation will be at energies 0.1-0.5 keV, accessible to soft X-ray detectors. The size of this fraction depends on the temperature of the boundary layer and the column density of absorbing gas.

If the boundary layer is optically thin, it will radiate primarily by thermal bremsstrahlung from a 1-30 keV plasma (Tylenda 1981). Half of this radiation will be intercepted by the white dwarf and accretion disk and re-radiated at longer wavelengths. The observable luminosity from the hot boundary layer plasma should be approximately one quarter of the total accretion luminosity. Most of this flux will be a hard X-ray flux at energies greater than 1 keV.

b. X-Ray Observations of Novae

The HEAO-1 soft X-ray survey of 102 novae did not detect X-ray emission in the 0.18-2.8 keV energy band from any of them, indicating that their soft X-ray luminosities are less than $10^{31}(d/100\ pc)^2$ ergs s^{-1} (CJN). Einstein observations of 14 of these novae in the 0.1-4.5 keV band are reviewed by Cordova and Mason (1983). Seven of these were detected with X-ray luminosities of 10^{31} - 10^{32} ergs s^{-1}. The novae detected had hard X-ray spectra, with most of the flux at energies greater than 1 keV. The remaining 7 novae were not detected, indicating their X-ray luminosities were less than 10^{32} ergs s^{-1}. There was no evidence for a soft X-ray component from any of the 14 novae observed. The conclusion from these observations is that these novae are weak, hard X-ray sources with X-ray luminosities less than 10^{32} ergs s^{-1} and source temperatures greater than 0.5 keV.

It is probable that the novae examined with HEAO-1 and Einstein constitute only a small fraction of the entire class of novae. Older novae, those whose last outbursts occurred more than 100 years ago, are probably much more numerous, since the recurrence time scale for nova outbursts is believed to be much greater than 100 years (Bath and Shaviv 1978). If so, there will be many older novae at distances nearer to the sun than are the observed novae. These novae have not been identified, but some of them would appear in sky surveys as serendipitous X-ray sources if their X-ray luminosities were sufficiently high. More stringent constraints on the X-ray luminosities of novae can be obtained from the lack of detections of older novae as serendipitous sources in X-ray sky surveys.

From the lack of detections of older novae in the HEAO-1 soft X-ray survey, CJN determined upper limits to the X-ray luminosity of the novae as a class of objects. They assumed the novae are uniformly distributed in the solar neighborhood with a number density n. If the novae typically have soft 30 eV blackbody spectra with a neutral hydrogen column density $N_H = 10^{20}$ cm^{-2}, CJN derived $L_x \lesssim 4 \times 10^{29} (n_{-4})^{-2/3}$ ergs s^{-1}, where n_{-4} is the number density of novae in units of 10^{-4} pc^{-3}. If the novae typically have hard 10 keV thermal bremsstrahlung spectra with $N_H = 10^{20}$ cm^{-2}, they derived $L_x \lesssim 10^{30} (n_{-4})^{-2/3}$ ergs s^{-1}. Becker (1981) made a similar analysis based on the lack of detections of older novae as serendipitous sources by the Einstein Imaging Proportional Counter. For the same hard X-ray spectrum considered by CJN, Becker derived $L_x \lesssim 5 \times 10^{29} (n_{-4})^{-2/3}$ for older novae as a class of objects.

The classical novae, considered as a class of X-ray sources, therefore appear to have X-ray luminosities much lower than expected if the boundary layer models for the X-ray emission from CVs are correct. This "nova problem", the discrepancy between the observed low L_x from novae and the higher L_x predicted by theory, has also been considered by Ferland et al. (1982a), who note that a resolution of this discrepancy is important for our understanding of the accretion process in CVs and the nature of the nova outbursts.

III. HEAO-1 CONSTRAINTS

The CJN and Becker analyses are limited in that a uniform distribution of novae was assumed and only two specific source spectra were considered. A more realistic treatment should account for scale heights in the distribution of novae in the solar neighborhood. Even more critical is the need to consider a wider range of source temperatures and column densities, since the sensitivity of the X-ray detectors often depends strongly on these parameters.

Another limitation is that constraints on the X-ray luminosity can be used to test boundary layer models only if a total accretion luminosity, hence a mass accretion rate, is assumed. A more useful constraint would be on the ratio of the boundary layer luminosity to the total accretion luminosity. Since boundary layer models predict that one quarter of the accretion luminosity should emerge as a boundary layer component, this ratio should be ~ 0.25, independent of the mass accretion rate.

In this section, I present an extension of the CJN work on constraints on the X-ray emission from novae, using results from the HEAO-1 soft X-ray survey, in which these limitations are overcome. A more realistic distribution of novae is used and a wide range of temperatures and column densities are examined. Rather than attempt to constrain the X-ray luminosity for an assumed number density and mass accretion rate, I attempt to constrain the fraction of the total accretion luminosity which can be radiated as an X-ray component solely as a function of the spectrum, temperature, and column density of that component. As a result, I am able to determine the types of X-ray spectra, temperatures, and column densities that are consistent with boundary layer models. I will show that the "nova problem" may be resolved if novae have optically thick boundary layers and higher column densities than have previously been supposed.

a. The HEAO-1 Survey

The HEAO A-2 low energy detectors (LEDs) have surveyed over 95% of the sky in the energy bands 0.18-0.44 keV, the "1/4 keV" band, and 0.44-2.8 keV, the "1 keV" band. As an all sky survey sensitive to the soft X-rays expected from an optically thick boundary layer and the harder X-rays expected from an optically thin boundary layer, it is a useful survey for examining the X-ray emission from the class of novae in the context of boundary layer models.

The HEAO A-2 LED source catalogue (Nugent et al. 1983; hereafter NEA) uses data collected in this survey by LED1. The results include new detections of 54 X-ray sources in the 0.18-2.8 keV energy band, of which 32 remain unidentified. Of these 32 sources, 22 are detected in the 1/4 keV band and 13 are detected in the 1 keV band, with 3 sources detected in both bands. These results set upper limits to the number of novae $\langle N_X \rangle$ which are expected to be detectable by LED1. It is improbable that many of the unidentified sources are novae, since none of the 82 identified LED sources are novae. A more realistic expectation is $\langle N_X \rangle \lesssim 1$.

Since LED1 is a proportional counter which records photon events (Rothschild et al. 1979), the sensitivity of the survey is initially measured as a count rate sensitivity. The characteristic count rate sensitivity of the survey in each band is determined by the criteria for inclusion of a source in the catalog. In the following analysis, 4.8 counts s^{-1} is used as the characteristic count rate sensitivity of the HEAO-1 soft X-ray survey in each band. This sensitivity corresponds to the 6.1σ significance criterion for the count rate intensity which was used for including a source in the catalog

(NEA). As a result of this survey, we may expect that there are $\lesssim 1$ novae detectable by LED1 at a count rate of 4.8 counts s^{-1}. This result can be applied to an analysis of the constraints on the X-ray emission from the class of novae.

b. Method of Analysis

Consider an X-ray source characterized by a photon spectrum dN/dE photons s^{-1} keV^{-1}. The luminosity of this X-ray component is:

$$L_{xc} = \int_0^\infty dE[E\ dN/dE].$$

L_{xc} is the total luminosity of the X-ray source at all energies, and not just the fraction of the luminosity in a given X-ray bandpass. The luminosity of the source in a given energy bandpass i is:

$$L_i = L_{xc} \cdot \frac{\int_i dE\ [E\ dN/dE]}{\int_0^\infty dE\ [E\ dN/dE]} = L_{xc}\ \beta_i,$$

where β_i is the fraction of L_{xc} which is radiated in bandpass i. Our measured parameter is c_i, the received count rate in the detector in bandpass i. We can determine L_i from c_i by:

$$L_i = 4\pi d^2 c_i \alpha_i,$$

where d is the distance to the source and α_i is a factor which converts the detected count rate to the energy flux which would be received at the detector in the absence of absorption. This factor depends on the spectral parameters dN/dE, kT, and N_H. See NEA for a discussion of the α_i conversion factor. Note that NEA call this factor d_i rather than α_i.

If a nova at a distance d is radiating an X-ray component characterized by dN/dE, kT, and N_H which is detected by LED1 in a bandpass i, the fraction of the total accretion luminosity radiated by the X-ray component is:

$$f \equiv L_{xc}/L_{acc} = \left(\frac{R}{GM\dot{M}}\right) \cdot \frac{4\pi d^2 c_i \alpha_i}{\beta_i} .$$

If we can determine a maximum distance d_x at which a nova is detectable by LED1, we can constrain f by:

$$f < \left(\frac{R}{GM\dot{M}}\right) \cdot \frac{4\pi d_x^2 \,(4.8 \text{ counts s}^{-1})\alpha_i}{\beta_i} .$$

Constraints on f can be directly applied to the boundary layer models. If the boundary layer is the source of X-ray emission from novae, the luminosity of the boundary layer is the equivalent of the luminosity of the X-ray component L_{xc}. From the predictions of the boundary layer models (§II), we then expect $f \sim 0.25$. It is convenient to express f as $f \lesssim \phi\delta$, where

$$\phi \equiv \left(\frac{R}{GM\dot{M}}\right) \cdot 4\pi d_x^2 \cdot (4.8 \text{ counts s}^{-1}) \cdot (10^{-11} \text{ ergs cm}^{-2} \text{ count}^{-1})$$

$$\delta \equiv \left(\frac{\alpha_i}{10^{-11} \text{ ergs cm}^{-2}\text{count}^{-1}}\right) \cdot \left(\frac{1}{\beta_i}\right) .$$

This separates f into the product of two functions, one of which, $\delta = \delta(\alpha_i, \beta_i) = \delta(dN/dE,\ kT,\ N_H)$, is solely a function of the source spectral parameters. The other function, ϕ, is not at all a function of these parameters. Since the white dwarf radius is determined by a mass-radius relation (Hamada and Salpeter 1961), ϕ is a function of the white dwarf mass, the mass accretion rate, and the maximum distance at which a nova is detectable by LED1: $\phi = \phi\ (M, \dot{M},\ d_x)$. I will demonstrate that d_x is related to M and $\dot{M}$ in such a way that ϕ is sharply constrained for the range of white dwarf masses and mass accretion rates expected for novae. Therefore f, unlike L_x, can be constrained as a function solely of the source spectral parameters dN/dE, kT, and N_H.

To determine d_x as a function of the white dwarf mass and mass accretion rate, I make two assumptions.

I assume that there have occurred 12 nova outbursts at distances less than 1 kpc during a recent 88 year interval. These estimates have been obtained from Duerbeck (1981). Using these estimates, the number density of novae which have had recent outbursts can be estimated.

I also assume that the nova outbursts are recurrent phenomena with a recurrence time scale τ_r which is a calculable function of the white dwarf mass and mass accretion rate. The outburst recurrence time scale is needed to calculate the number density of all novae from the number density of novae which have had recent outbursts. For a derivation of $\tau_r\ (M, \dot{M})$, I have relied on the basic model describing the nova outburst as a thermonuclear runaway in the hydrogen rich white dwarf envelope (Gallagher and Starrfield 1978) and on the work of Nariai and Nomoto (1979) on the evolution of a hydrogen envelope in an accreting white dwarf. For a discussion of this work, see Nomoto

(1982).

The results from the calculations of Nariai and Nomoto are represented in Figure 1, where the outburst recurrence time scale τ_r is shown for mass accretion rates ranging from 10^{-11} M_o yr^{-1} to 10^{-7} M_o yr^{-1} and for white dwarf masses of 1.0, 1.3, and 0.6 solar masses. The local number density of novae n, which is proportional to τ_r (see Appendix), is also shown.

If these assumptions are correct, we can determine the maximum distance d_x at which a nova can be detected by LED1 from

$$I(d_x) = \frac{1.1 \langle N_x \rangle}{\tau_r},$$

where d_x is in units of kpc, $\langle N_x \rangle$ is the expectation number of novae detectable by LED1, τ_r is in units of years, and

$$I(d) \equiv \int_o^d dr \int_o^{2\pi} d\theta \, [r \, e^{-[(100+r^2+20r\cos\theta)^{1/2}/3.4]}(1-e^{-5(d^2-r^2)^{1/2}})]$$

A description of the derivation of $I(d_x)$ is given in the Appendix. I(d) is plotted in Figure 2. For d<<200 pc, I is proportional to d^3; for d>>200 pc, I is proportional to d^2. This behavior is a result of choosing a z scale height of 200 pc for the novae. Values of I(d) are tabulated by Jensen (1982). I(d) is a measure of the relative number of novae located at various distances d. For example, $I(d = 0.1 \text{ kpc}) = 4.6 \times 10^{-4}$ while $I(d = 1 \text{ kpc}) = 0.1518$ so that there are ~ 330 times as many novae within 1 kpc as there are within 100 pc. The absolute number of novae located within a given distance d depends also on N_o, τ_o, and τ_r (see Appendix).

Since τ_r is a function of the white dwarf mass and mass accretion rate, we can determine d_x as a function of M, $\dot{M}$, and the expected number of detectable novae $\langle N_x \rangle$. An estimate of $\langle N_x \rangle \lesssim 1$ is derived from the lack of detection of novae in the HEAO-1 soft X-ray survey. In Figure 3, I show the dependence of d_x on the mass and mass accretion rate if we expect one nova to be near enough to be detectable by LED1 ($\langle N_x \rangle = 1$). There is not a large deviation from the trend $d_x^2 \propto \dot{M}$. Therefore, ϕ, which is proportional to $d_x^2/\dot{M}$, is relatively insensitive to the mass accretion rate. Since δ is not a function of mass and mass accretion rate, the dependence of f on M and $\dot{M}$ is the same as the dependence of ϕ on M and $\dot{M}$.

The weak dependence of ϕ on mass and mass accretion rate is illustrated in Figure 4. The relatively small variation in ϕ for the entire range of white dwarf mass and mass accretion rate shows that the constraints on f, the ratio of the total accretion luminosity which can be radiated as an X-ray component, are relatively insensitive to the mass and mass accretion rate. Since the wide range of white dwarf masses and mass accretion rates considered here will account for the expected masses and mass accretion rates for the novae, the upper limits I derive for f can be assumed to be applicable to the novae as a class of objects, even though most novae are not directly observed and in fact have not been identified. As a class of objects, novae are therefore characterized by

$$f \lesssim \phi_{max} \cdot \frac{\alpha_i}{10^{-11}\ \text{ergs cm}^{-2}\text{count}^{-1}} \cdot \frac{1}{\beta_i},$$

where ϕ_{max} is chosen as the maximum value of ϕ for a given white dwarf mass. For a given mass, the mass accretion rate which maximizes ϕ is chosen. Thus, the value of f derived for a given white dwarf mass is always an upper limit. For M = 1 solar mass, $\phi_{max} = 4.8 \times 10^{-4}$; for M = 0.6 solar mass, $\phi_{max} = 8.7 \times 10^{-4}$; for M = 1.3 solar mass, $\phi_{max} = 7.2 \times 10^{-4}$.

With ϕ_{max} determined, the types of source spectra consistent with boundary layer models are constrained by the requirement

$$\phi_{max} \cdot \frac{\alpha_i(dN/dE,\ kT,\ N_H)}{10^{-11}\ \text{ergs cm}^{-2}\ \text{count-1}} \cdot \frac{1}{\beta_i(dN/dE,\ kT)} \gtrsim 0.25.$$

Two types of source spectra are considered.

1. Thermal bremsstrahlung[2]: $dN/dE \sim \frac{g(E)}{E} e^{-E/kT}$, appropriate for the consideration of optically thin boundary layers. Gaunt factors g(E) are taken from Karzas and Latter (1961).

2. Blackbody: $dN/dE \sim E^2/(e^{E/kT} - 1)$, appropriate for the consideration of optically thick boundary layers.

Conversion factors α_i (kT, N_H) in the 1 keV and 1/4 keV bands are calculated by NEA for thermal bremsstrahlung spectra (their Figure 8) and for blackbody spectra (their Figure 10). Note that NEA call these factors d_i

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[2]For kT less than 3 keV, radiative recombination and line transitions in an optically thin plasma cannot be neglected and will have an effect on dN/dE (Blumenthal and Tucker 1974). α_i and β_i are not available for recombination spectra so this effect cannot be accounted for precisely. The effect on α_i and β_i will not be sufficiently large to change in any important way the conclusions (§IIIc) regarding optically thin boundary layers (Jensen 1982).

rather than α_i. For a given spectrum, the band with the smaller α_i/β_i is chosen, since it produces a tighter constraint on f.

C. Results of the Analysis

The constraints on f, the fraction of the total accretion luminosity which can be radiated as an X-ray component by novae, are the principal results of the analysis. The upper limits to f as a function of source temperature and column density for a thermal bremsstrahlung spectrum are shown in Figure 5. The upper limits to f for a blackbody spectrum are shown in Figure 6.

These figures illustrate f for the case of a one solar mass white dwarf under the assumption $\langle N_X \rangle = 1$. In this case, $\phi_{max} = 4.8 \times 10^{-4}$. To obtain f for a specific mass and mass accretion rate, one can read $\phi(M,\dot{M})/\phi_{max}$ from Figure 4 and adjust f accordingly. For example, if we choose a white dwarf mass of 1.3 solar masses and a mass accretion rate of 10^{-8} M_0 year^{-1} as typical, we find $\phi = 7.0 \times 10^{-4}$. Therefore $\log_{10}$ f should be increased by 0.16 over the $\log_{10}$f shown in Figures 5 and 6. Tables of $\phi(M,\dot{M})$ are given in Jensen (1982). Errors in the derivation of f due to errors in the estimations of the expected number of novae detectable by LED1, $\langle N_X \rangle$, the number of recent nova outbursts at distances less than 1 kpc, N_0, and the dependence of the outburst recurrence timescale τ_r on mass and mass accretion rate, may be deduced roughly from the relation $f \propto (\langle N_X \rangle / N_0 \ \tau_r)^{0.7}$. If the assumption $\langle N_X \rangle = 1$ is in error, it is more likely to be an overestimate. Therefore, unless Nariani and Nomoto seriously overestimate $\tau_r(M,\dot{M})$, errors in the estimates of $\langle N_X \rangle$, N_0 and τ_r should tend to overestimate f so that the upper limits to f derived here should be valid.

i) Constraints on f

For a given spectrum, temperature, and column density N_H, the upper limit to f, the fraction of the total accretion luminosity which can be radiated as an X-ray component from novae, can be read from Figures 5 and 6. For example, in the case of a 30 eV blackbody spectrum with $N_H = 10^{20}$ cm^{-2}, Figure 6 shows that $\log_{10}f < -2.5$, or $f < .003$. Therefore, if novae are characterized as one solar mass white dwarfs with 30 eV blackbody components and column densities of 10^{20} cm^{-2}, less than 0.3% of the total accretion luminosity can emerge from that component. If more than 0.3% emerged as a 30 eV blackbody component, we would expect to see more than one nova with LED1. If N_H is typically as high as 10^{21} cm^{-2}, the constraint is relaxed to $f < 0.24$. Therefore, if 25% of the total accretion luminosity emerged as a 30 eV blackbody flux with $N_H = 10^{21}$ cm^{-2}, we would expect to detect one nova with LED1.

Since we expect $f \sim 0.25$ for the boundary layer component (§II), values of (kT, N_H) consistent with a boundary layer component lie above the horizontal dashed lines marking $f = 0.25$ in Figures 5 and 6. It can be seen from these figures that f is less than 0.25 except for extreme temperatures and large column densities. These results can be applied to constrain the nature of the boundary layers in novae.

ii) Optically Thin Boundary Layers

From Figure 5, it can be seen that if novae have optically thin boundary layers, very low temperatures and high column densities are required for consistency with the HEAO-1 constraints. For a column density $< 10^{22}$ cm^{-2}, kT < 250 eV is required. Boundary layer temperatures this low would require low viscosities and very low mass accretion rates (Tylenda 1981) and would not be hard X-ray sources even if they could be produced. If novae have optically thin boundary layers hot enough to produce the hard X-ray fluxes observed from the selected novae in the Einstein IPC sample, column densities greater than 2×10^{22} cm^{-2} are required to explain the lack of detections of novae by the

HEAO-1 LED1. Unless the column densities to the nearest novae are this large, the HEAO-1 constraints show that only a small fraction of the rotational energy in the boundary layer can emerge as hard X-rays. It is improbable that the column densities are this large, since the hard X-ray spectrum would then show an absorption turnover at energies greater than 1 keV. Such turnovers are not observed in the spectra of CVs with observed hard X-ray fluxes.

iii) Optically Thick Boundary Layers

As noted earlier, $f \lesssim .003$ for the blackbody spectrum considered by CJN ($kT = 30$ eV, $N_H = 10^{20}$ cm^{-2}). If novae have optically thick boundary layers, they must be characterized by lower temperatures and/or higher column densities. For a column density of 10^{21} cm^{-2}, boundary layer temperatures $\lesssim 30$ eV are consistent with the HEAO-1 constraints. Pringle's (1977) optically thick boundary layer model predicts temperatures of 15-30 eV. Therefore, the view that novae typically have optically thick boundary layers is consistent with the HEAO-1 constraints if the column densities to these boundary layers are typically $\gtrsim 10^{20.5}$-10^{21} cm^{-2}.

IV. DISCUSSION

Ferland et al. (1982a) suggest that the most likely solution to the "nova problem" is either a source of optical radiation in excess of the radiation produced by accretion, such as a reprocessed flux from a hot white dwarf, or a boundary layer structure greatly different from that predicted by current models. Sources of large optical excess can result in low ratios of X-ray to optical luminosity, even if the boundary layer converts a large fraction of the energy liberated by accretion into X-rays. Such sources have no effect on the ratio of X-ray to accretion luminosity, however. It is this parameter which is constrained by my analysis. By recasting the "nova problem" as a deficiency in L_X/L_{acc}, rather than L_X/L_{opt}, my analysis shows that the solution cannot be a source of excess optical radiation.

The preceding analysis of the HEAO-1 constraints on the X-ray emission from novae suggests an alternative solution which can be reconciled with current boundary layer models. The discrepancy between the low X-ray luminosities observed from novae and the higher luminosities expected from the boundary layer is resolved if novae have optically thick boundary layers with temperatures ~ 15-30 eV and column densities $\gtrsim 10^{20.5}$-10^{21} cm^{-2}. In that case, we do not observe a strong hard X-ray flux from novae because an optically thick boundary layer will not be a hard X-ray source. Likewise, we do not observe a strong soft X-ray flux from novae, even though it is produced in the boundary layer, because most of this flux is absorbed by an intervening column of gas, and re-radiated at longer wavelengths.

a) The Importance of Photoelectric Absorption

The constraints on the soft X-ray emission from novae are very sensitive to column densities in the range 10^{20} - 10^{21} cm^{-2} because the cross section for photoelectric absorption ranges from 3 x 10^{-21} cm^{-2} to 10^{-20} cm^{-2} for photons in the 1/4 keV energy band of LED1. Therefore, optical depths of unity occur for column densities of 1-3 x 10^{20} cm^{-2}. The effect of column density on the energy flux in the 180-280 eV band received from a 30 eV blackbody is shown in Figure 7. Most of the flux detectable by LED1 from a 30 eV blackbody is received in this energy band. For a column density of 10^{20} cm^{-2}, less than half of the 180-280 eV flux is absorbed, but more than 99% of this flux is absorbed by a column density of 10^{21} cm^{-2}.

The effect of this much larger absorption is found in the conversion factors from received count rates to flux at the source, α. For a 30 eV blackbody with $N_H = 10^{20}$ cm^{-2}, $\alpha \sim 10^{-11}$ ergs cm^{-2} count^{-1}, whereas for a 30 eV blackbody with $N_H = 10^{21}$ cm^{-2}, $\alpha \sim 10^{-9}$ ergs cm^{-2} count^{-1}. A 30 eV blackbody must therefore be 100 times as luminous to be detectable by LED1 if $N_H = 10^{21}$ cm^{-2} than if $N_H = 10^{20}$ cm^{-2}. For column densities greater than 10^{21} cm^{-2} the absorption is so large that the probability of detecting a nova with LED1 is very small. For example, if novae have 30 eV optically thick boundary layers with N_H as large as 3×10^{21} cm^{-2}, the probability of detecting soft X-rays from a nova with LED1 is less than 1%.

CJN did not consider column densities greater than 10^{20} cm^{-2}. The discrepancy they found between the low soft X-ray luminosities inferred from non-detections of novae and the higher luminosities expected from optically thick boundary layers is resolved if column densities are greater.

b) The Circumstellar Gas

Since the nearest novae are probably at distances $\lesssim$ 100 pc, it is unlikely that interstellar column densities are greater than 10^{20} cm^{-2}. If novae have optically thick boundary layers with kT ~ 15-30 eV, the required large absorption of the soft X-rays in the boundary layer flux means that there must be enough absorbing gas in the system to produce column densities $\gtrsim 10^{20.5}$ cm^{-2}. The flux from the boundary layer should have an effect on the ionization of this gas. Ferland et al. (1982b) applied photoionization models to fit the ultraviolet and optical line spectra of the nova V603 Aquilae. They found better fits for models in which the line forming region is not exposed to an EUV/soft X-ray flux expected from an optically thick boundary layer. Kallman's (1983) photoionization analysis of the abundances of SiIV, CIV, and NV in the ultraviolet line forming region of the dwarf nova TW Virginis in outburst also results in the conclusion that a strong EUV/soft X-ray boundary layer flux cannot be illuminating the gas responsible for the ultraviolet lines.

These results should be regarded with caution, however. Ferland et al. assume a constant density $n_e = 10^{10}$ cm^{-3}. This is probably a poor assumption. For example, King et al. (1983) find $n_e \gtrsim 10^{12}$ cm^{-3} for the line forming region in the nova-like variable UX UMa. It is probable that there are large density gradients in the circumstellar gas of CVs, with $n_e \gtrsim 10^{12}$ cm^{-3} at the base of a wind and n_e much smaller farther out in the wind. Kallman assumes that the Si IV, C IV, and N V absorption features are all formed in the same region. If this is not the case, his conclusions must be modified. For UX UMa, King et al. (1983) find that the C IV, Si IV, and N V lines have different eclipse behavior, suggesting that the lines are not formed in identical regions. As King et al. note, a fully self-consistent model for the circumstellar gas in CVs is required to constrain the nature of the boundary layer radiation.

Ferland et al. (1982a) discussed the possibility that X-ray emission is suppressed by absorbing gas in nova systems. They concluded that there is not sufficient absorbing gas in the corona of V603 Aquilae to suppress the X-ray emission and that this scenario was therefore an unattractive explanation for the "nova problem". This conclusion may not be correct. While the column densities of 10^{21} - 10^{22} cm^{-2} inferred for the V603 Aquilae model corona of Ferland et al. (1982b) are not sufficient to absorb a 1 - 10 keV hard X-ray flux, they are sufficient to cut off a 0.1 - 0.5 keV soft X-ray flux unless most of the helium is doubly ionized.

McCray and Lamb (1976) have proposed the existence of an opaque shell around the neutron star in Her X-1 to explain the strong soft X-ray flux observed from Her X-1 as reprocessed flux from the central hard X-ray source. If a similar process occurs in CV_s, in which a central soft X-ray flux irradiates an optically thick region which reprocesses it into longer wavelengths, boundary layer models can be reconciled with X-ray observations. If, on the other hand, it can be demonstrated that such a process is unlikely, a reconsideration of boundary layer theory may be required.

c) Other Types of CVs

The preceding analysis of HEAO-1 constraints on the X-ray emission from novae cannot be used for other CV subclasses. The nova subclass is uniquely suitable for an analysis constraining the fraction of the accretion luminosity radiated by an X-ray component because the number density of the novae is a function of the white dwarf mass and mass accretion rate, through its dependence on the outburst recurrence time scale (§IIIb).

The Einstein IPC observations of selected novae, nova-like variables, and dwarf novae may help us to understand the nature of their boundary layers, when considered in the context of the constraints on the boundary layers in novae. Particularly useful is the ratio of the received flux from the hard X-ray component in the 0.1-4.0 keV band, f_X, to the received flux in the visual band, f_V. Mason and Cordova (1982) note that the dwarf novae in quiescence have larger f_X/f_V ratios than the dwarf novae in outburst. Although there is more scatter in f_X/f_V for the novae and nova-like variables, as a group they tend to have f_X/f_V ratios closer to those of dwarf novae in outburst than dwarf novae in quiescence.

It is more difficult to use f_X/f_V ratios to test boundary layer models than it is to use ratios of the X-ray component luminosity to the total accretion luminosity, because the ratio of visual band flux to total bolometric flux may depend on poorly determined factors such as reprocessed fluxes from the white dwarf, the accretion disk, and the secondary star. It is tempting though to infer from the similarity in f_X/f_V between the novae, the nova-like variables, and the dwarf novae in outburst that nova-like variables and dwarf novae in outburst have boundary layers similar to nova boundary layers. Since the dwarf novae in quiescence are believed to have lower mass accretion rates, it may be that they produce hard X-rays in an optically thin boundary layer while the boundary layers in novae, nova-like variables, and dwarf novae in outburst are optically thick soft X-ray producers.

Subclasses of CVs which are not believed to have accretion disk boundary layers, such as the AM Herculis stars, have not been considered in this work.

d) The Hard X-Ray Source

If novae, nova-like variables, and dwarf novae in outburst typically have optically thick boundary layers, what is the source of the weak hard X-ray flux observed from them? The HEAO-1 constraints cannot directly identify this source, but they do constrain the fraction of the accretion luminosity which can be radiated by this source for the novae and, by inference, for the nova-like variables and dwarf novae in outburst. For example, if we adopt $N_H = 10^{21}$ cm^{-2} as typical, Figure 5 shows that less than 1% of the accretion luminosity can be radiated by a 1-10 keV optically thin plasma. Even for N_H as large as 10^{22} cm^{-2}, less than 3% can be radiated by the hard X-ray source.

Where in a CV system can we find a hot thin plasma which radiates only a small fraction of the gravitational energy released by accretion? Jensen *et al.* (1983) have suggested that the weak hard X-ray flux observed from the nova-like variable TT Arietis is produced in an accretion disk corona. If only a small fraction of the energy dissipated in the accretion disk and boundary layer is transported to the corona, it can explain why only a small fraction of the accretion luminosity is radiated by the hard X-ray source. This explanation may apply to the weak hard X-ray fluxes generally observed from novae, nova-like variables, and dwarf novae in outburst.

e) Concluding Remarks

The lack of detection of novae in the HEAO-1 LED1 survey, and the observation of very weak hard X-ray fluxes from novae, nova-like variables, and dwarf novae in outburst by the Einstein IPC, can be consistent with boundary layer models for the accretion process in cataclysmic variables if novae, nova-like variables, and dwarf novae in outburst typically have optically thick boundary layers with boundary layer temperatures kT = 15-30 eV and neutral hydrogen column densities $N_H \gtrsim 10^{20.5}$-10^{21} cm^{-2}.

If so, the boundary layer is the source of a strong soft X-ray flux which is highly absorbed by circumstellar gas and re-radiated at longer wavelengths. A fully self-consistent model for the circumstellar gas in CVs is desirable to investigate this possibility.

The weak hard X-ray fluxes observed from these systems are unlikely to be produced in the boundary layer, but may be produced in an accretion disk corona.

ACKNOWLEDGMENTS

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APPENDIX

The number of nova outbursts N_o which will occur during a time interval τ_o at a distance $< d_o$ is given by

$$N_o = \frac{\tau_o}{\tau_r} \int_0^{d_o} dr \int_0^{2\pi} r d\theta \int_0^{(d_o^2 - r^2)^{1/2}} n(r,\theta,z)\, dz \quad \text{(A1)}$$

where τ_r is the characteristic time scale for the recurrence of a nova outburst in a single nova system and $n(r,\theta,z)$ is the number density of the novae as a function of cylindrical coordinates centered at the sun. The ratio τ_o/τ_r is the fraction of novae which are expected to have outbursts during a time interval τ_o. The integration of the number density over a sphere with radius d_o centered at the sun gives the total number of novae within a distance d_o

$$N(d_o) = \int_0^{d_o} dr \int_0^{2\pi} r d\theta \int_0^{(d_o^2 - r^2)^{1/2}} n(r,\theta,z)\, dz. \quad \text{(A2)}$$

If we define d_x as the maximum distance at which the X-ray emission from a nova can be detected by the HEAO-1 LED1 detector, the integration of the number density over a sphere with radius d_x centered at the sun gives us the number of nova systems $\langle N_x \rangle$ detectable by the HEAO-1 soft X-ray survey:

$$\langle N_x \rangle = N(d_x) = \int_0^{d_x} dr \int_0^{2\pi} r d\theta \int_0^{(d_x^2 - r^2)^{1/2}} n(r,\theta,z)\, dz. \quad \text{(A3)}$$

In the CJN and Becker treatments, $n(r,\theta,z)$ = constant = 10^{-4} pc^{-3}. A more careful analysis should account for scale heights in the distribution of the novae. For my analysis, I use:

$$n(\rho,\phi,z) = Ae^{-(\rho/3.4\ \text{kpc})}\ e^{-(z/0.2\ \text{kpc})} \tag{A4}$$

where (ρ,ϕ,z) are cylindrical coordinates centered at the galactic center and A is an arbitrary constant. The scale heights $h_\rho = 3.4$ kpc and $h_z = 0.2$ kpc are estimated from the distribution of gas and dust in the galaxy (Allen 1973). Transforming $n(\rho,\phi,z)$ in coordinates centered at the galactic center to $n(r,\theta,z)$ in coordinates centered at the sun (ρ =10 kpc, z = 0), we derive

$$n(r,\theta,z) = Ae^{-[(100 + r^2 + 20\ r\cos\theta)^{1/2}/3.4]}\ e^{-5z} \tag{A5}$$

where r and z are in units of kpc.

Combining equations A1, A3, and A5, we derive:

$$\frac{\langle N_x\rangle}{N_o} = \frac{\tau_r I(d_x)}{\tau_o\ I(d_o)} \tag{A6}$$

where:

$$I(d) \equiv \int_0^d dr \int_0^{2\pi} d\theta\ [r\ e^{-[(100+r^2+20r\cos\theta)^{1/2}/3.4]}(1 - e^{-5(d^2-r^2)^{1/2}}) \tag{A7}$$

and d is in units of kpc. See Jensen (1982) for details.

Using the estimates $N_o = 12$, $\tau_o = 88$ years, $d_o = 1$ kpc, we have:

$$\frac{\langle N_x\rangle}{12} = \frac{\tau_r}{88\ \text{years}}\ \frac{I(d_x)}{I(1.0)} \tag{A8}$$

Since I(1.0) = 0.1518, we derive:

$$I(d_x) = \frac{1.1\ \langle N_x\rangle}{(\tau_r/1\ \text{year})} \tag{A9}$$

which is the equation for d_x used in §IIIb.

From equations A1, A5, and A7, we have:

$$N_o = \frac{\tau_o}{\tau_r} \; A \; I \; (d_o) \qquad \text{(A10)}$$

If d_o is in units of kpc, A is in units of kpc^{-3}. From our estimates N_o = 12, τ_o = 88 years, and d_o = 1 kpc, hence $I(d_o)$ = 0.1518, we can estimate A:

$$A = 9 \times 10^{-9} \left(\frac{\tau_r}{1 \text{ year}}\right) \; pc^{-3} \qquad \text{(A11)}$$

and n:

$$n(\rho,\phi,z) = 9\text{x}10^{-9}\left(\frac{\tau_r}{1 \text{ year}}\right) \; e^{-\rho/3.4 \text{ kpc}} \; e^{-z/0.2 \text{ kpc}} \; pc^{-3} \qquad \text{(A12)}$$

The estimated number density of the novae is proportional to the outburst recurrence time scale because we estimate the number density of all novae from the number density of observed novae. We must therefore multiply the observed number density by the inverse of the fraction of all novae which have been observed. This inverse fraction is estimated as τ_r/τ_o.

In the neighborhood of the sun ($\rho \approx$ 10 kpc, z << 200 pc), the number density of the novae is then estimated to be

$$n \approx 4.7 \times 10^{-10} \left(\frac{\tau_r}{1\ \text{year}}\right) \text{pc}^{-3} \qquad \text{(A13)}$$

This relation is reflected in Figure 1.

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FIGURE CAPTIONS

Figure 1 - The dependence of τ_r, the timescale for the recurrence of a nova outburst, on the white dwarf mass and mass accretion rate, according to the models of Nariai and Nomoto (1979). The local space density of novae, n, which is proportional to τ_r, is also indicated.

Figure 2 - The function I(d) is shown for distances between 10 pc and 2 kpc. I(d) is a measure of the relative number of novae located at distances < d from the sun. The estimated vertical scale height in the distribution of novae (h_z = 200 pc) is indicated. For $d \ll h_z$, $I \propto d^3$; for $d \gg h_z$, $I \propto d^2$.

Figure 3 - The dependence of d_x, the maximum distance at which a nova is detectable by the HEAO-1 soft X-ray survey, on the white dwarf mass (M) and mass accretion rate ($\dot{M}$). Since it is derived under the assumption that one nova is near enough to be detectable by HEAO-1, d_x is also the expected distance to the nearest nova. The trend $d_x^2 \propto \dot{M}$ is indicated by the dashed line.

Figure 4 - The dependence of $\phi \equiv (GM\dot{M}/R)^{-1}\, 4\pi\, d_x^2$ (4.8 counts s^{-1}) (10^{-11} ergs cm^{-2} $count^{-1}$) on the white dwarf mass (M) and mass accretion rate ($\dot{M}$). The relatively small variation in ϕ over the wide range of M and $\dot{M}$ means that the fraction of the total accretion luminosity which can be radiated as an X-ray component by novae, f, can be well constrained independent of mass and mass accretion rate.

Figure 5 - Upper limits to f, the fraction of the total accretion luminosity that can be radiated by novae as a thermal bremsstrahlung spectrum, as a function of the temperature (kT) and neutral hydrogen column density N_H of the spectrum. Contours of constant N_H are shown. The $\log_{10} N_H$ (cm^{-2})

is indicated for each contour. The horizontal dashed line marks $f \leq 0.25$. The HEAO-1 observations are consistent with a boundary layer source only for thermal bremsstrahlung spectra characterized by temperatures and column densities lying above the dashed line.

Figure 6 - Upper limits to f, the fraction of the total accretion luminosity that can be radiated by novae as a blackbody spectrum, as a function of the temperature (kT) and neutral hydrogen column density (N_H) of the spectrum. Contours of constant N_H are shown. The $\log_{10} N_H$ (cm^{-2}) is indicated for each contour. The horizontal dashed line marks $f \leq 0.25$. The HEAO-1 observations are consistent with a boundary layer source only for blackbody spectra characterized by temperatures and column densities lying above the dashed line.

Figure 7 - The fraction of the 180-280 eV energy flux emitted from a 30 eV blackbody which is received after passing through the indicated column densities. This fraction becomes very sensitive to column densities greater than $\sim 10^{20}$ cm^{-2}.

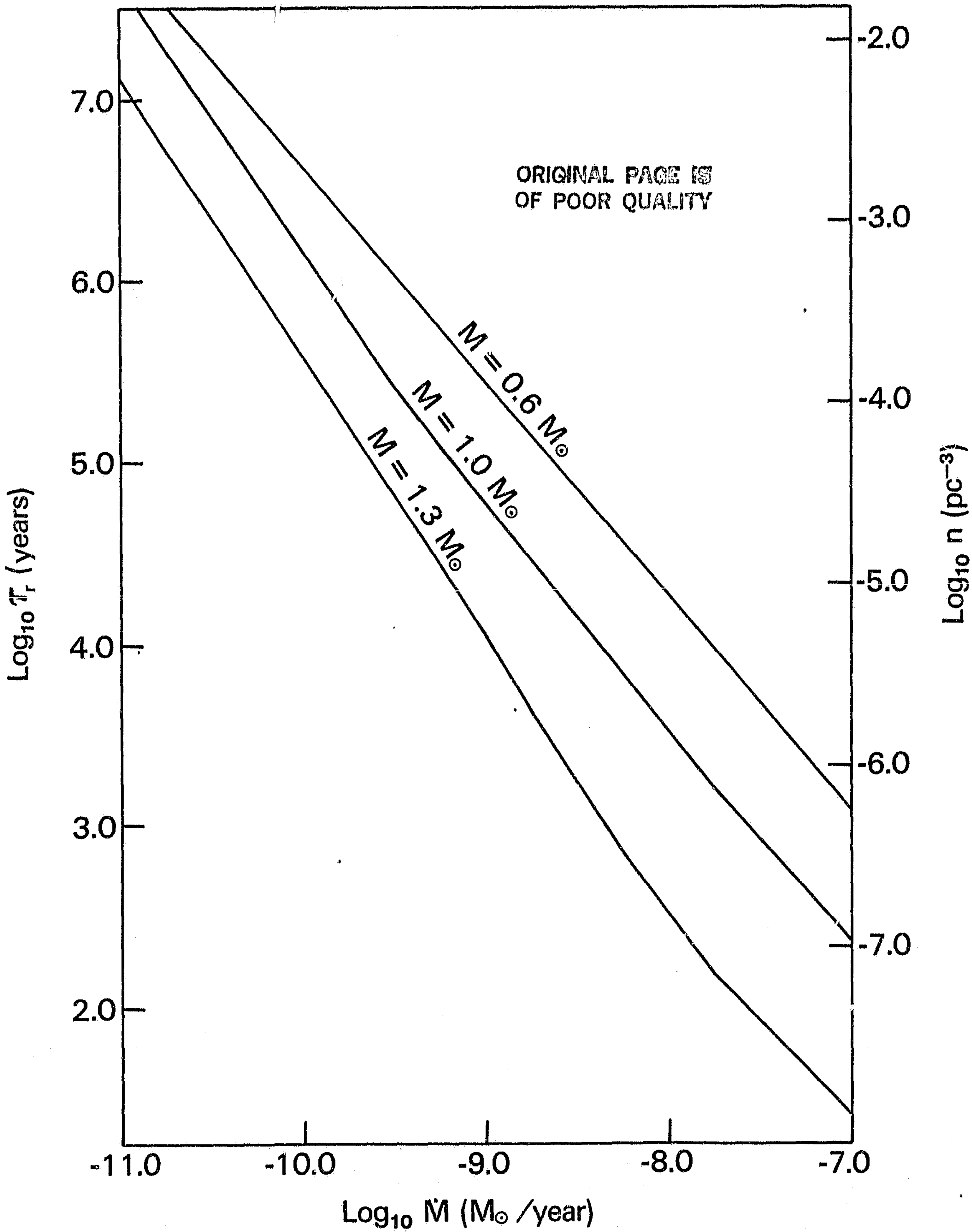

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Figure 1

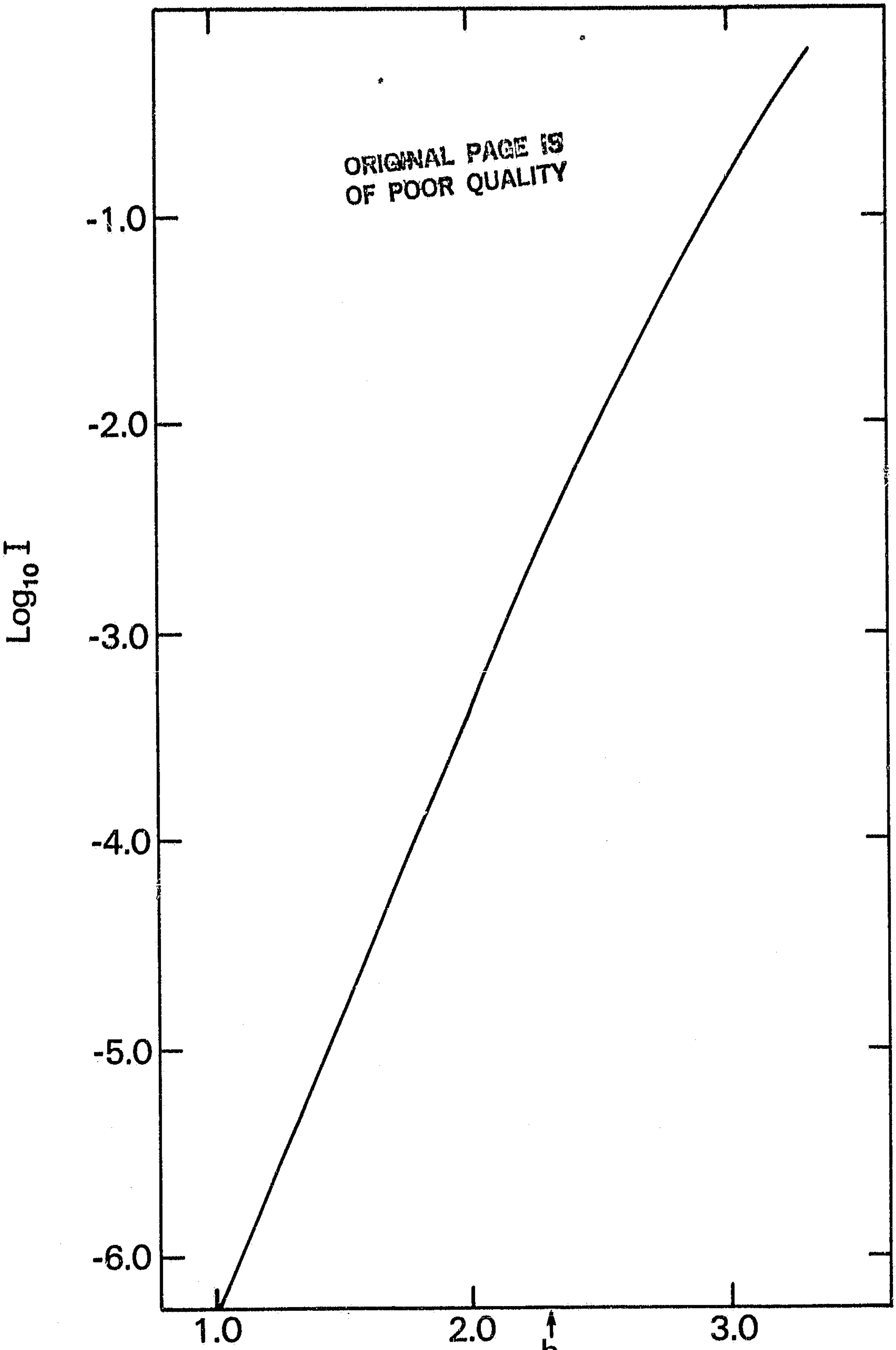

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Figure 2

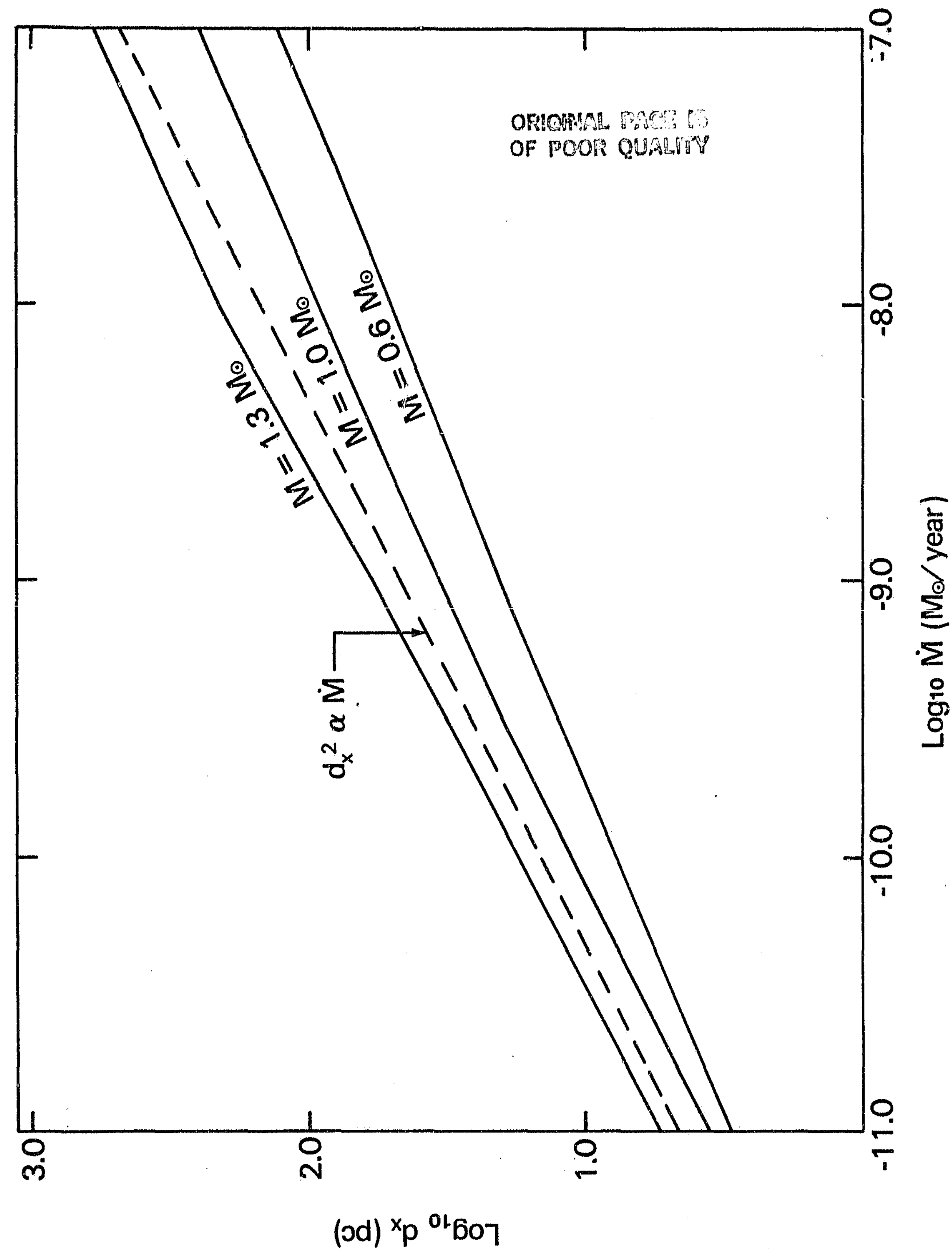
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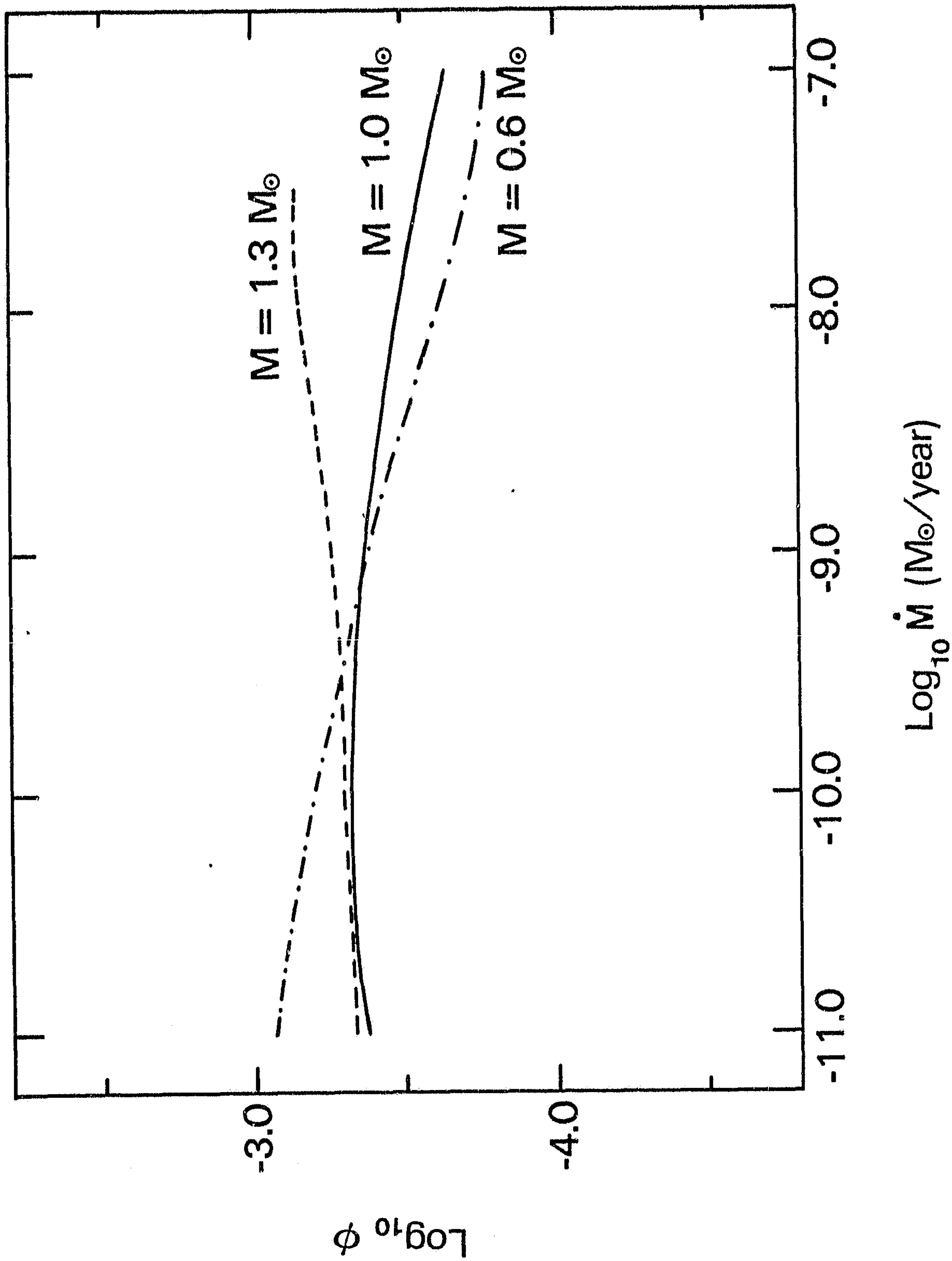
Figure 3



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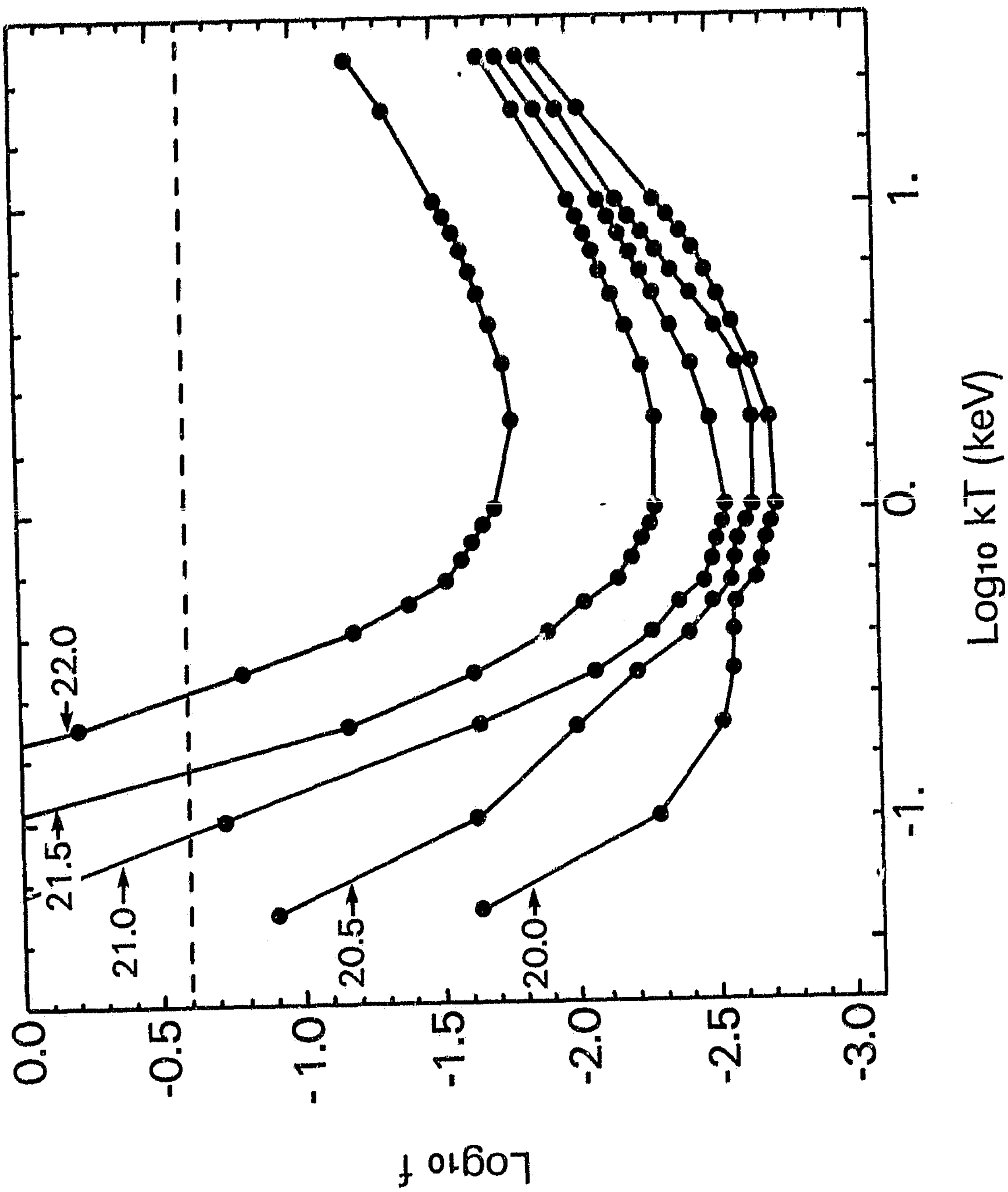

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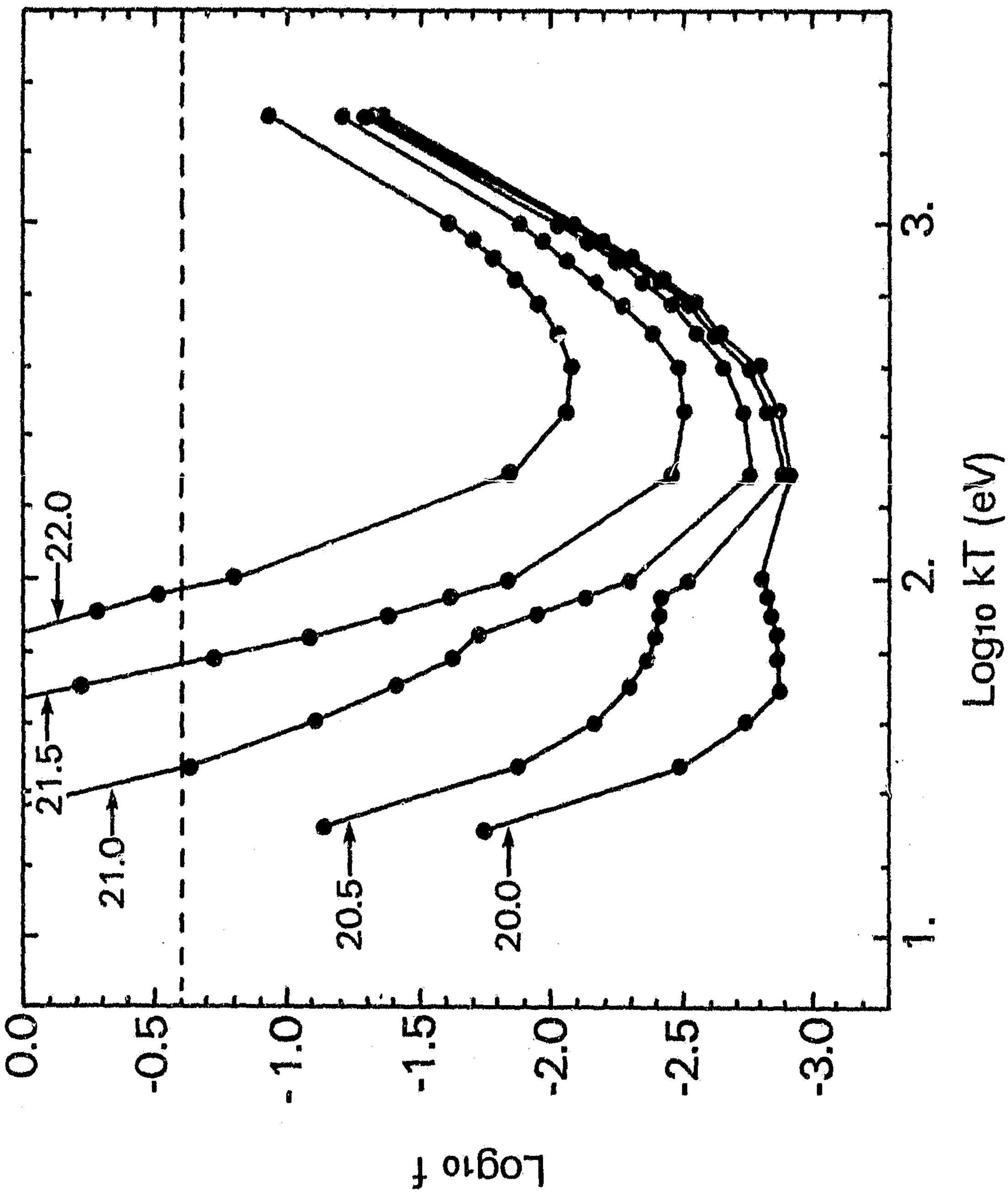

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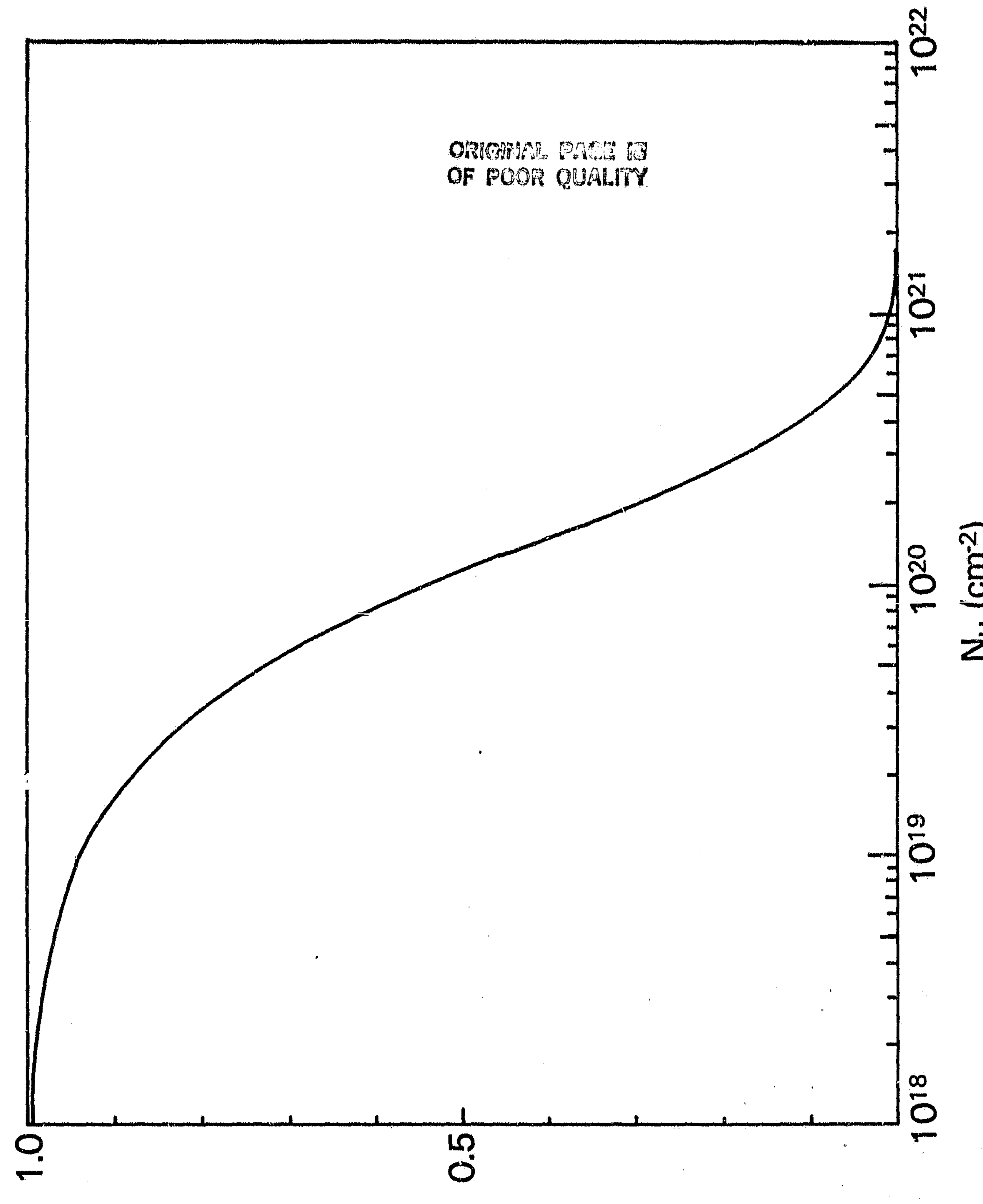
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N_H (cm^{-2})

Figure 7

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