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ACCRETION TURNOFF AND RAPID EVAPORATION OF VERY LIGHT SECONDARIES IN LOW-MASS X-RAY BINARIES

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ABSTRACT

Low magnetic field neutron stars in binaries can be spun up to millisecond periods by near Eddington limit accretion from very light companions. Observations of X-ray sources indicate that accretion terminates relatively abruptly ($\ll 10^8$ yr) and suggest that companions which are very light are often (perhaps always) eliminated on a similar time scale leaving behind solitary millisecond radiopulsars. Illumination of such companions by various kinds of radiation from the neighborhood of the neutron star after accretion has terminated or during accretion, when spin up or subsequent partial spin down occurs (as accretion falls), is considered here as a crucial feature in understanding these observations. If a neutron star's spun-up period approaches 10^{-3} s, pulsar kHz radiation can quench accretion by pushing surrounding plasma away from the neutron star and may leave the companion to be evaporated by the high-energy radiation component expected from an "isolated" millisecond radiopulsar. Expected accretion-powered MeV γ-rays and $e^{\pm}$ winds may also be effective in evaporating dwarf companions. Neutron star spin down energy release may sustain the power in these radiation mechanisms even while accretion falls. Accretion-powered soft X-rays may speed the mass loss of highly evolved dwarf companions, particularly those with a large fraction of carbon and oxygen.

Subject headings: gamma rays: general — pulsars — stars: accretion — stars: evolution — stars: neutron — X-rays: binaries

I. INTRODUCTION

The canonical description of a very low mass X-ray binary (LMXB) is a neutron star (primary) accreting mass from a very light degenerate companion (secondary) driven to overflow its Roche lobe by the loss of angular momentum from the system. In the simplest and original models, gravitational radiation carried away the angular momentum (Faulkner 1971). In these models the accretion rate dropped with the diminishing secondary's mass. Accretion-driven X-ray luminosity would gradually drop far below the near Eddington limit regime and the secondary would survive well beyond the age of the Galaxy. But the following three different kinds of observations argue against such a model.

a) Solitary Millisecond Pulsars

A possible argument against the simple canonical model is the observation of solitary millisecond pulsars. These have the same characteristics as pulsars in binaries which appear to have been accretion disk spunup by their companions. The solitary pulsar former companion may have been tidally disrupted (Ruderman and Shaham 1983, 1985). However, there are problems in reaching unstable configurations with very light companions during the 10^{10} yr age of the universe (Jeffrey 1986). Alternatively, the secondary may have been eliminated in an earlier common envelope phase so that the very light mass regime of a LMXB is not achieved (Bonsema and van den Heuvel 1984).

b) Survival of Spunup Millisecond pulsars

Very rapidly spinning low field radio pulsars (with surface dipole field $B_s \approx 5 \times 10^8$ G and mass $M \approx M_\odot$) are usually considered to have been spunup by near Eddington limit accretion from companions (Alpar *et al.* 1982). To transfer enough angular momentum from a surrounding accretion disk to the neutron star, this strong accretion phase must last more than 10^7 yr. If the accretion is slowly diminished the neutron star spin period (P) will continually adjust to the accretion rate as described by the approximate equality

$$P \approx 10^{-3} L_{38}^{-3/7} \times (B_s/5 \times 10^8 \text{ G})^{6/7} \text{ s} \tag{1}$$

for an accretion X-ray luminosity

$$L_{38} = \frac{GM\dot{M}/R}{10^{38} \text{ ergs s}^{-1}} . \tag{2}$$

To preserve a neutron star's millisecond period after spin-up by near Eddington limit accretion, subsequent accretion must be reduced sufficiently rapidly that there is not enough time during that reduction for a large spin angular momentum loss from the

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neutron star back to the now more slowly rotating accretion disk. Then the accretion turn-off time must satisfy

$$\tau_{\rm turnoff} < \frac{I(2\pi/P)}{N} \approx \frac{10^7}{L_{37}^{9/7}} \times (B_s/5 \times 10^8 \text{ G})^{-2/7} \text{ yr} , \tag{3}$$

where I is the neutron star moment of inertia and N is the spin-down torque. In equation (3) the spin-down torque is taken from Ghosh and Lamb (1979) with the dimensionless torque function of the "fastness parameter" set equal to -1, and P is taken from equation (1). Angular momentum loss from gravitational radiation does not drop rapidly enough ($\ll 10^8$ yr) to freeze a millisecond pulsar's period. The removal of angular momentum from a LMXB by gravitational radiation can maintain the Roche lobe overflow of the secondary at or above the neutron star primary's Eddington limit needed to preserve a millisecond P only as long as the secondary's mass (m) exceeds $\sim 10^{-1}\ M_\odot$ (Figs. 1 and 2).

c) *LMXB Luminosities*

Most LMXBs are observed to have X-ray luminosities near the Eddington limit of an accreting neutron star, $L_X \approx 10^{38}$ ergs s^{-1} (Long and van Speybroek 1983). The corresponding mass accretion rate $\dot{M} \approx 10^{-8}\ M_\odot$ yr^{-1}, so a very low mass secondary ($m < 10^{-1} M_\odot$) could sustain this phase for only 10^7 yr. Fewer LMXBs are observed with 10^{37}–10^{36} ergs s^{-1} and none with $L_X < 10^{35}$ ergs s^{-1}. The initial strong near Eddington limit accretion of LMXBs must drop by more than several orders of magnitude in much less than 10^6 yr to account for this deficit (as well as to preserve millisecond pulsar periods).

Accretion onto the neutron star, and neutron star spin-down can be the sources of various kinds of radiation part of which could illuminate the secondary. Such radiation can induce strong evaporative winds and may qualitatively change the evolution of LMXBs when the secondary's mass falls below $10^{-1}\ M_\odot$ (see Ruderman *et al.* 1987, hereafter RSTE). In § II we consider the

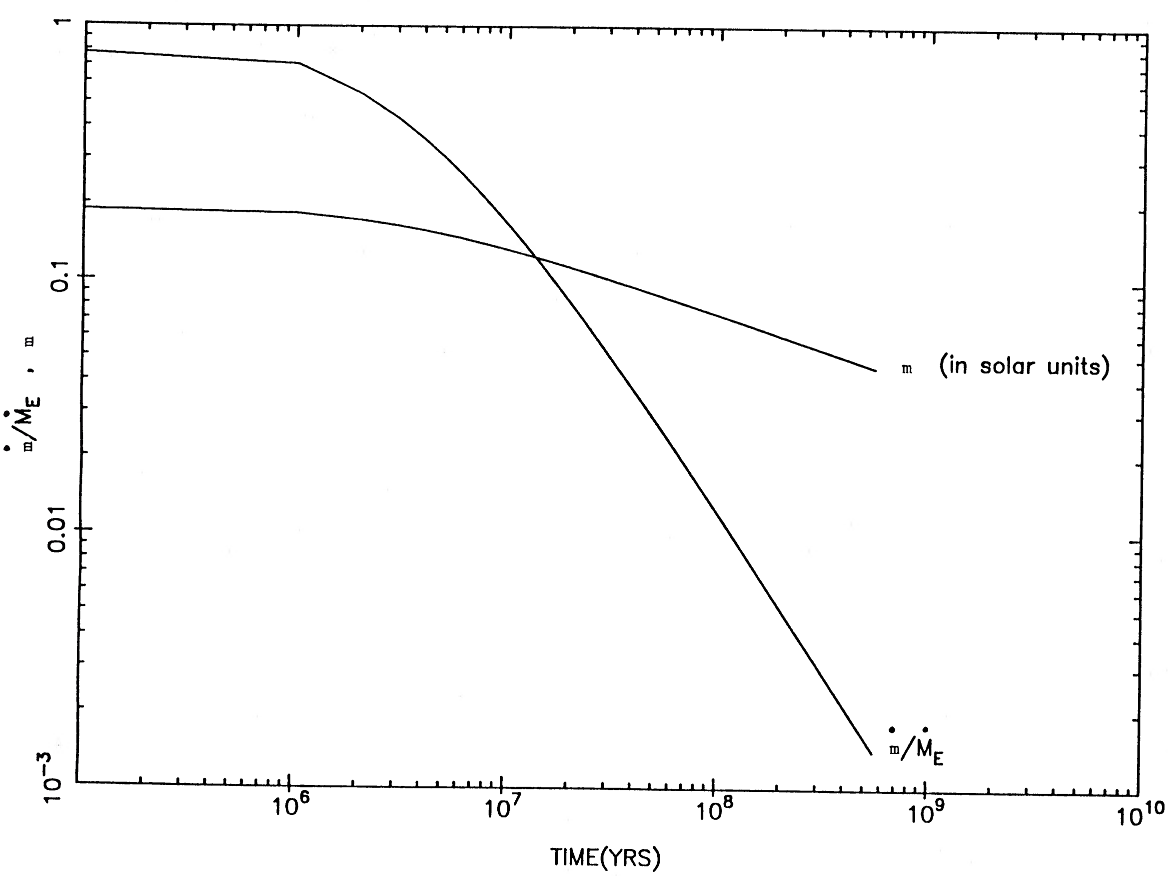

FIG. 1*a*

FIG. 1.—LMXB evolution controlled entirely by angular momentum loss from gravitational radiation with a H secondary dwarf. The secondary mass is m and Ω is the neutron star angular spin velocity whose evolution is computed with the Ghosh and Lamb torque (Ghosh and Lamb 1979) for a neutron star with a dipole surface magnetic field $B_s = 5 \times 10^8$ G. (*a*) Secondary mass m and mass transfer rate $|\dot{m}|$ vs. time computed according to gravitational radiation evolution (Li *et al.* 1980). (*b*) Evolution of angular speed Ω and luminosities computed with the Ghosh-Lamb model. $L_{\rm accr} = GM\dot{M}/R$ is the dissipated energy-loss rate due to accretion when all Roche lobe overflow is accreted onto the neutron star, and $L_{\rm spindown} = I\Omega\dot{\Omega}$ is the released neutron star spin-down power. The total $L_{\rm total}$ is the sum of the two and is the maximum possible X-ray luminosity for all energy loss that appears in that form. The initial angular speed of the neutron star has been set equal to an equilibrium value equal to 4200 rad s^{-1} for an initial mass transfer rate equal to the Eddington limit. (*c*) Spin-down power computed from equation (26) for a binary containing a H white dwarf secondary. The initial angular speed has been set equal to ~ 8400 rad s^{-1}. The evolution of the neutron star angular speed Ω and of the accretion luminosity are also shown.

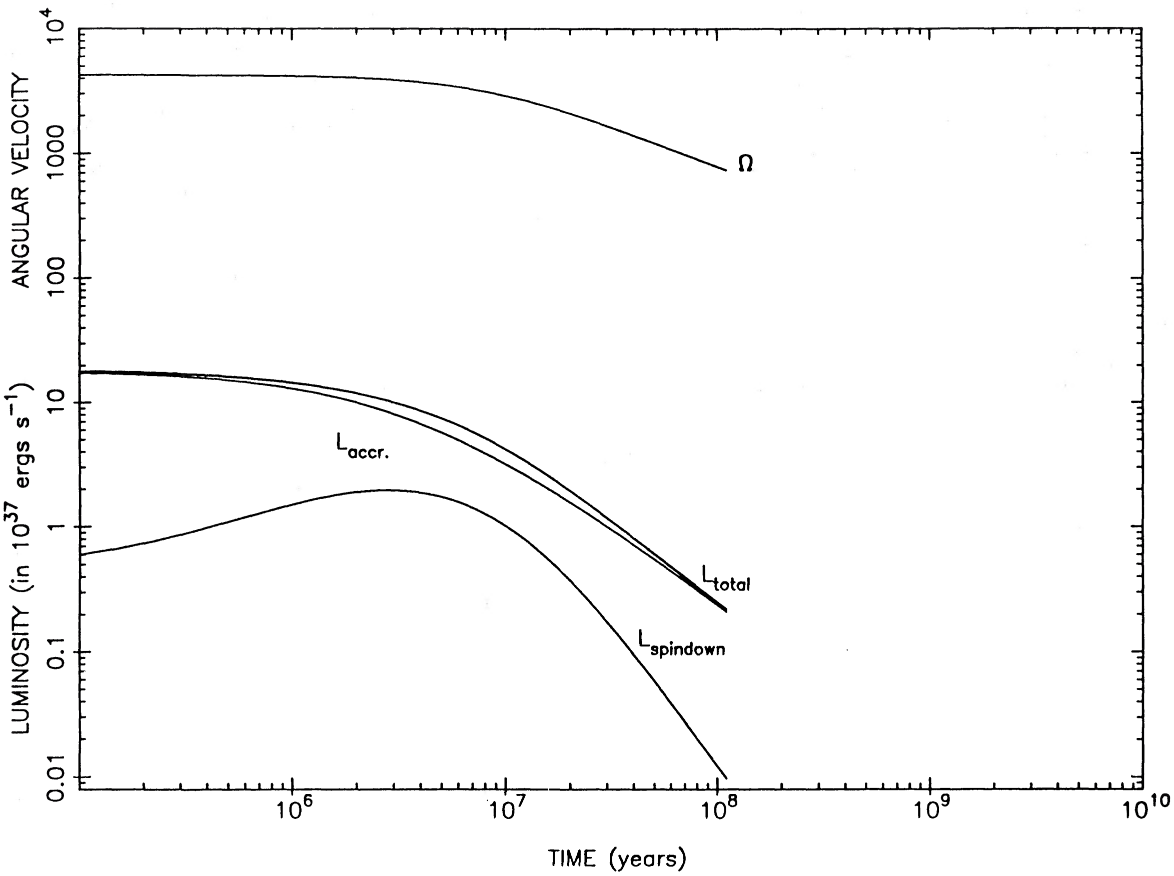
ANGULAR VELOCITY
LUMINOSITY (in 10^{37} ergs s^{-1})
TIME (years)
Ω
$L_{accr.}$
L_{total}
$L_{spindown}$

FIG. 1b

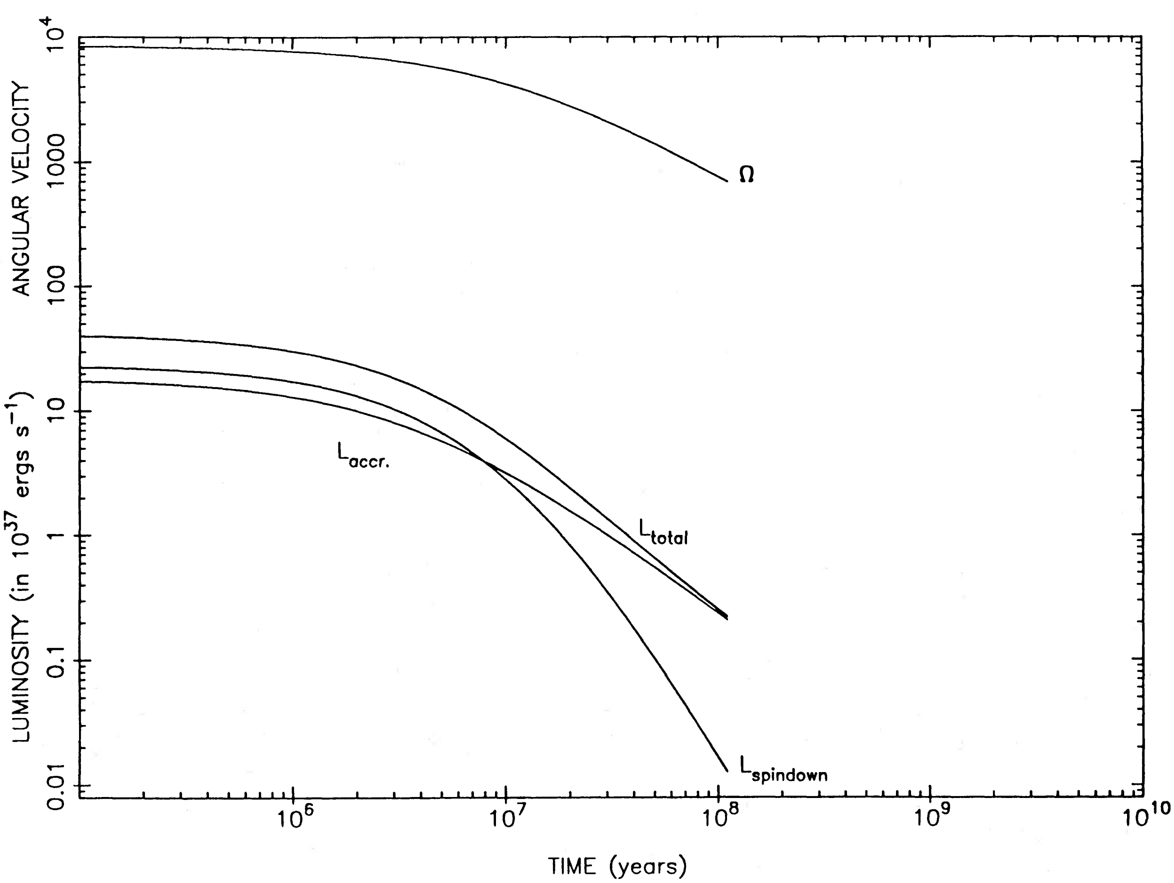
ANGULAR VELOCITY
LUMINOSITY (in 10^{37} ergs s^{-1})
TIME (years)
Ω
$L_{accr.}$
L_{total}
$L_{spindown}$

FIG. 1c

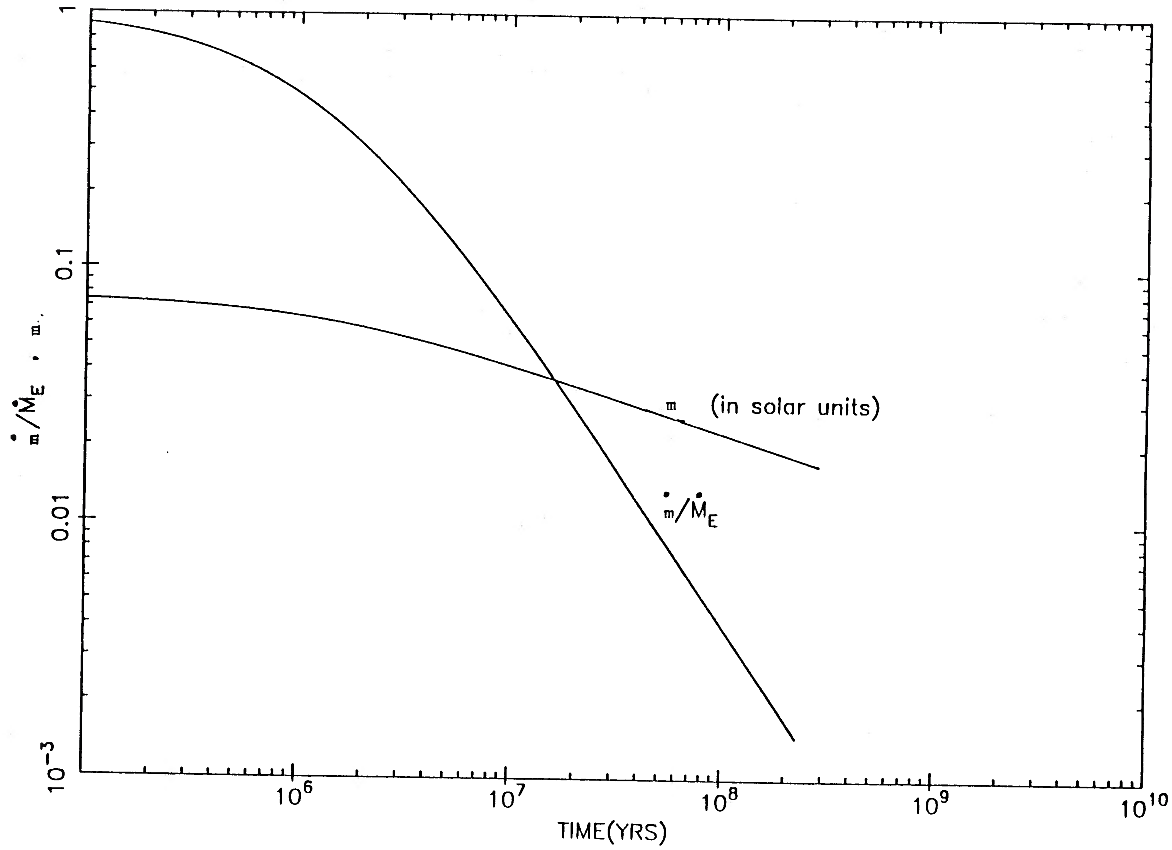

FIG. 2a

FIG. 2.—LMXB evolution as in Fig. 1 for a He secondary dwarf. (*a*) Secondary mass and mass accretion rate vs. time. (*b*) Angular speed and luminosities as defined in Fig. 1*b* computed according to the Ghosh-Lamb model for the spin-down power. (*c*) Spin-down power computed from equation (26) for a binary containing a He white dwarf. The evolution of the neutron star angular speed Ω and of the accretion luminosity are also shown.

different kinds of fluxes which may come from the neighborhood of low magnetic field neutron stars in LMXBs and the evaporative winds such fluxes could induce in companion stars which they can illuminate.

A case of special importance occurs when the accretion rate drops sufficiently (even if temporarily) that the inner edge of the accretion disk moves out beyond the light-cylinder radius ($cP/2\pi$) of a very rapidly rotating neutron star. This is discussed in § III. Accretion may be quenched completely as the radiation pressure of the spinning neutron star pushes out the surrounding plasma and reveals a millisecond quasi-solitary pulsar. Once this is achieved, it may no longer be possible for accretion onto the neutron star to be reestablished even if the conditions that previously sustained it are again effective. The ways in which a millisecond pulsar in a binary with a very light companion can evaporate that companion are then discussed.

In § IV we consider the consequences for the secondary and for X-ray luminosity of the spin-down energy removed from a maximally accretion spun-up neutron star when its accretion rate begins to drop. This source of radiated power and its effects are very much more important for the low-field high-spin pulsars of a LMXB than they are for high-field, lower spin X-ray pulsars.

Section V describes the evolution of secondaries with relatively high metal abundances driven by the primary's accretion powered X-rays. In the second part of this section similar possibilities are summarized for the consequences of expected MeV γ-ray radiation on dwarf secondaries which have been discussed elsewhere (RSTE).

The general picture that emerges is of the richness of LMXB mechanisms and phenomena that are consequences of the neutron star radiation during spin-up, in steady state, or during spin-down. In particular, there are a number of seemingly attractive possibilities for understanding both the occasional elimination of the very light secondaries when P is particularly small and relatively abrupt quenching of LMXB neutron star accretion when the companion mass is much less than 10^{-1} $M_\odot$.

II. INCIDENT FLUXES THAT CAN EVAPORATE LIGHT SECONDARIES

Part of the radiation powered by accretion spin-up of a low-mass, low magnetic field neutron star (primary) or by the post-accretion spin-down of that primary can be intercepted by the secondary. Such radiation may include (RSTE) (1) keV X-rays from the accretion disk and the neutron star surface, (2) MeV γ-rays from the interface region between the neutron star corotating magnetosphere and the Keplerian accretion disk around it, (3) an $e^{\pm}$ wind from a postaccretion residual millisecond pulsar primary, (4) a Crab pulsar–like γ-ray flux from such pulsars, and (5) a possible early Crab-like X-ray flux spectrum if these pulsars were originally spun-up to periods $P < 10^{-3}$ s.

We shall assume that the secondary which may be exposed to these fluxes has the radius $\hat{R}$ versus mass m relationship indicated in figure 3 (Zapolsky and Salpeter 1969). For $m > 10^{-3}$ $M_\odot$ for He and $m > 3 \times 10^{-3}$ $M_\odot$ for H stars we approximate the secondary

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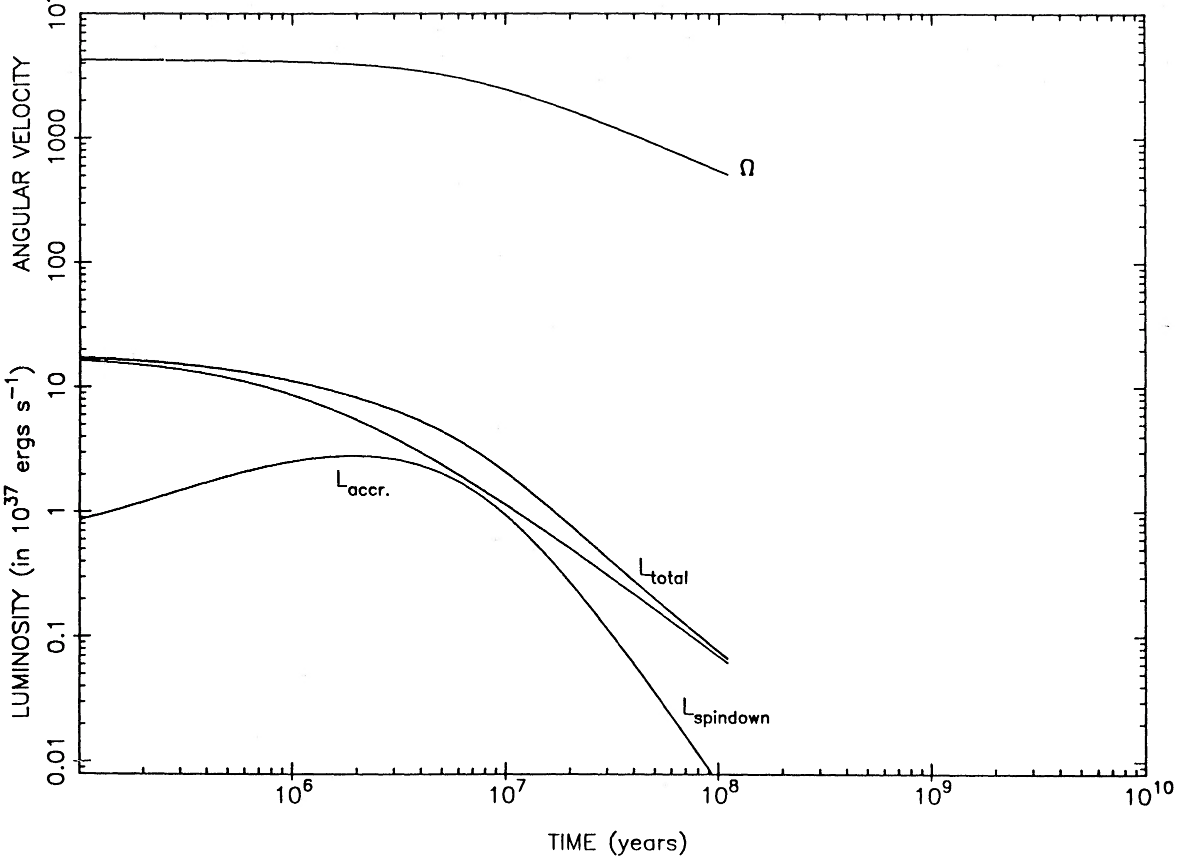

FIG. 2*b*

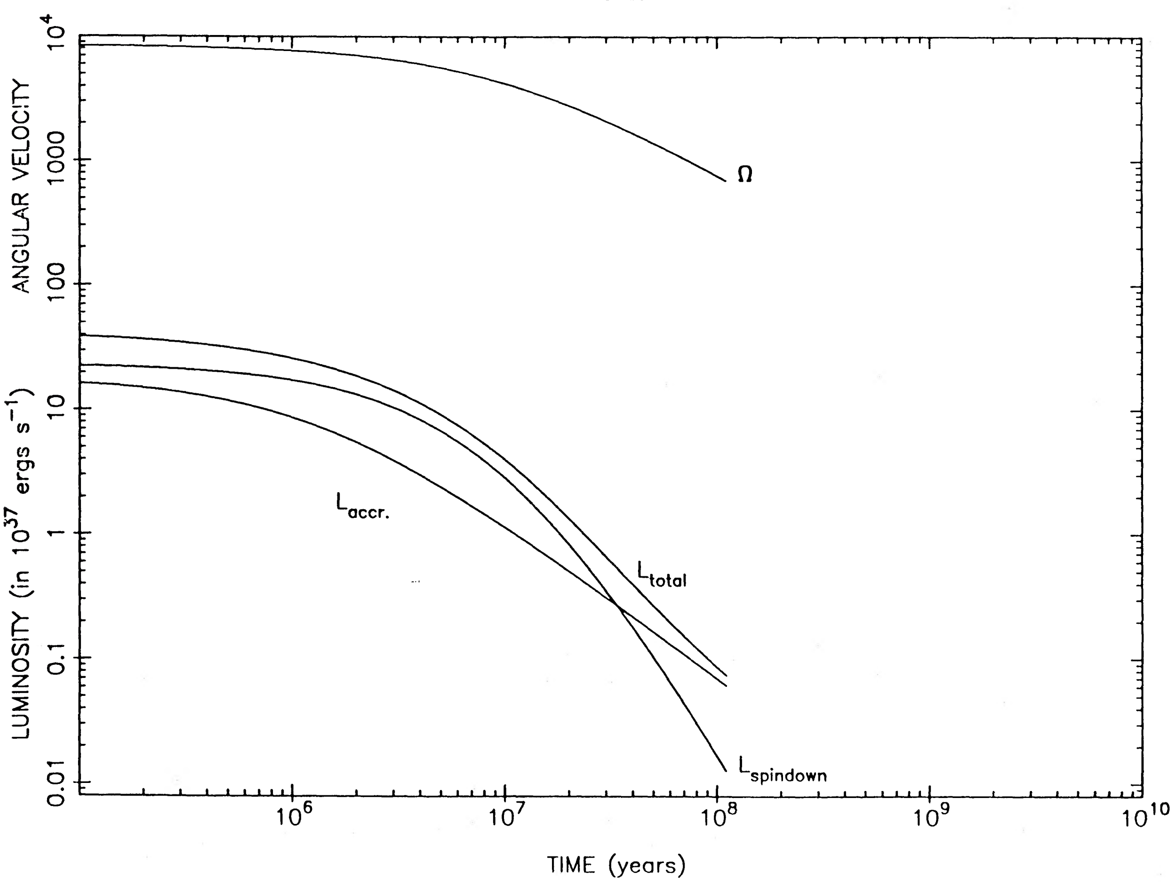

FIG. 2*c*

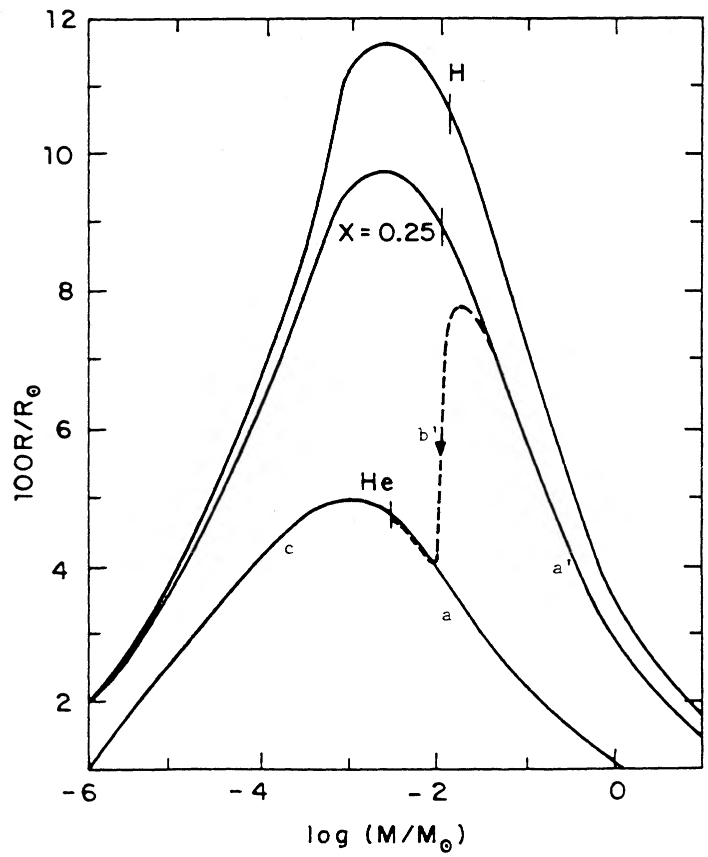

FIG. 3.—Radius vs. mass for light degenerate H and He secondaries (Zapolsky and Salpeter 1969). (The dotted line *a'b'* is that for a H white dwarf which has a He core from previous main-sequence burning.) The line *c* is for such light stars (planets) that electrons are largely bound into atoms and $\hat{R} \approx m^{1/3}$, corresponding to constant density.

as a degenerate dwarf whose pressure is that of free electrons so that

$$\hat{R} \approx R_D \times (m/M_\odot)^{-1/3} , \tag{4}$$

with $R_D \approx 1.2 \times 10^9$ cm for a H dwarf and $R_D \approx 3.5 \times 10^9$ cm for a He one. At lower masses we take the secondary to be planet-like with constant density and

$$\hat{R} \approx 10^2 \times R_D \times (m/M_\odot)^{1/3} . \tag{5}$$

Each of the above radiation fluxes would induce evaporative winds from a secondary which intercepts any part of that flux. We shall approximate the magnitudes and velocities of these winds as indicated below.

a) X-Rays

According to Basko *et al.* 1977 and London, McCray and Auer 1981, a flat spectrum of incident keV X-rays (0.1–30 keV) will result in an emerging particle wind whose velocity v_w is around the secondary's escape velocity,

$$v_e \approx \left(\frac{Gm}{\hat{R}}\right)^{1/2} \approx 10^7 \left(\frac{m}{10^{-2}\, M_\odot}\right)^{2/3} \text{cm s}^{-1} , \tag{6}$$

for $m > 10^{-3}\, M_\odot$. Energy deposition from the incident X-ray flux is mainly from photoelectric absorption by K-shell electrons still bound to the metals (C, N, O) in the hot outer atmospheres. The evaporative mass flow in the wind has been taken to be (London *et al.* 1981; London and Flannery 1982)

$$\dot{m}_w \approx -10^{-18} \xi \left(\frac{m}{10^{-2}\, M_\odot}\right)^{-2/3} \left(\frac{X_M}{10^{-3}}\right) \hat{L}_X \text{ g s}^{-1} , \tag{7}$$

where $\hat{L}_X$ is the power of the intercepted incident X-rays and X_M is the fractional metal abundance in the X-ray–illuminated outer atmosphere of the secondary. The factor ξ is the ratio of the soft (0.2–1 keV) X-ray intensity to the total incident spectrum in L_X, relative to the same ratio for the Her X-1 X-ray pulsar.

b) MeV γ-Rays

We adopt an estimate given elsewhere (RSTE):

$$\dot{m}_w \approx -10^{17} f \hat{L}_\gamma \text{ g s}^{-1} , \tag{8}$$

where $f < 1$, which gave a wind velocity

$$v_w \gtrsim v_e . \tag{9}$$

For incident γ-ray energies far above 1 MeV, $\dot{m}_w$ would be less by a factor $\sim E^{-1}$ ln (E) with E the γ-ray energy in MeV.

c) $e^\pm$ Winds

When a millisecond pulsar illuminates a companion, a variety of different kinds of radiation would be expected in the incident flux in addition to a strong electromagnetic wave at the pulsar rotational frequency. In the case of the young Crab (and probably also Vela) pulsar there is strong evidence that a very large fraction of the pulsar spin-down energy loss is carried away by a 10^{12} eV $e^\pm$ wind (Kennel and Coroniti 1984) and, as discussed below, a similar wind may be expected from a millisecond pulsar. The conversion of some of the power of such an incident wind into that of evaporative mass loss depends sensitively on the target secondary's magnetic field. If there is no field the $e^\pm$ main energy deposition is several 10^2 g cm^{-2} into the stellar atmosphere where it is ineffective in driving an evaporative wind (unless the incident power exceeds the secondary's Eddington limit). The case of a modestly magnetized secondary will be discussed in § III.

d) Super-Eddington Illumination

If the illumination $\hat{L}$ intercepted by the exposed hemisphere of a very light secondary exceeds that hemisphere's Eddington limit, then the above estimates are no longer valid. As long as the Thomson cross section σ_T for momentum loss of outgoing UV/soft X-rays exceeds that for the incident radiation and

$$\hat{L} > \hat{L}_{\text{Eddington}} = 2\pi G m m_{\text{H}} c/\sigma_{\text{T}} = 5 \times 10^{35} (m/10^{-2}\ M_\odot) \text{ ergs s}^{-1} , \tag{10}$$

where m_{H} is the mass per electron in the outer atmosphere, then

$$\dot{m}_w \approx \frac{2\hat{L}}{v_w^2} \approx 10^{-14} (m/10^{-2}\ M_\odot)^{-1} \hat{L} \text{ g s}^{-1} . \tag{11}$$

In equation (11) it is assumed that the evaporative wind velocity is near the secondary escape speed. If inequality (10) holds the estimate of equation (11) will be used for very strong incident γ-ray or energetic $e^\pm$ fluxes. When the incident illuminating flux has the same scattering cross-section as that of the outward emission it powers (e.g., X-rays incident onto the emitted from a secondary's H/He atmosphere) the inward as well as outward push of radiation must be considered. A net outward radiation push is achieved only for incident angles relative to local vertical $\theta > \cos^{-1}(\frac{2}{3})$ (see Fig. 4). For very strong incident radiation, two-thirds of the power incident upon an illuminated secondary hemisphere would drive a super-Eddington wind from two-thirds of that surface.

III. SECONDARY EVAPORATION AFTER PULSAR TURN ON

If, for any reason, the LMXB neutron star accretion rate $\dot{M}$ is suppressed abruptly enough to put the accretion disk Alfvén radius R_{A} well beyond the spinning neutron star's light-cylinder radius (c/Ω), the accretion can be permanently and completely quenched. The magnetic field energy density of a nonaligned spinning neutron star at the distance r from the star is

$$\frac{B^2}{8\pi} \approx \frac{\dot{E}_p}{4\pi r^2 c} \tag{12}$$

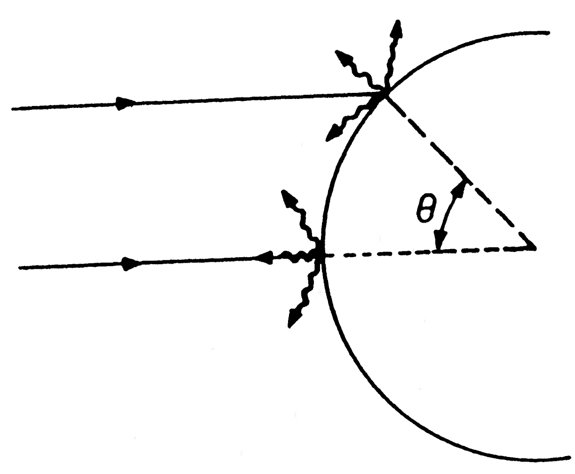

FIG. 4.—Geometry for incident and emitted radiation of a secondary illuminated by a parallel beam

for $r \gg c/\Omega$, and

$$\frac{B^2}{8\pi} \approx \left(\frac{c}{\Omega r}\right)^4 \frac{\dot{E}_p}{4\pi r^2 c} \approx \frac{B_s^2}{8\pi}\left(\frac{R}{r}\right)^6 \tag{13}$$

for $r \ll c/\Omega$, with the neutron star spin-down power $\dot{E}_p$ given by

$$\dot{E}_p \approx 3 \times 10^{37}\left(\frac{P}{10^{-3}}\right)^{-4}\left(\frac{B_s}{5 \times 10^8}\right)^2 \text{ ergs s}^{-1} , \tag{14}$$

with B_s the neutron star's surface dipole field, and R its radius. The steady state accretion disk boundary radius R_A is determined by equating the spin-up torque $\dot{M}(GMr)^{1/2}$ of equation (25) to the spin-down torque B^2r^3 of equation (26). Thus at $r = R_A$

$$B^2 \approx \frac{1}{2}\dot{M}\left(\frac{GM}{r^5}\right)^{1/2} . \tag{15}$$

For $r \gg c/\Omega$, where equation (12) is appropriate, the left-hand side of equation (15) falls more slowly with growing r than does the right-hand side. If r equals the distance to the secondary, the left-hand side exceeds the right-hand side, then the pulsar's spin-down radiation pressure may keep evaporated Roche lobe spill-over matter from the secondary from ever reaching the primary. Even if there is another solution which satisfies equation (15), well within the light-cylinder where equation (13) holds, that configuration may not be reachable (if there is no solution with $R < R_A < c/\Omega$ there is also none for $R_A > c/\Omega$). Therefore accretion can be permanently quenched under either of two conditions:

Condition 1:

$$\dot{M} < \frac{B_s^2 R^6 \Omega^4}{c^5} \approx 10^{-10}\left(\frac{\dot{E}_p}{10^{37} \text{ ergs s}^{-1}}\right) M_\odot \text{ yr}^{-1} . \tag{16}$$

In this case there is no finite Alfvén radius solution for the disk as the pulsar pushes away surrounding plasma.

Condition 2:

$$\dot{M} < \frac{B_s^2 R^6 \Omega^4}{c^5} \approx 10^{-5}\left(\frac{\dot{E}_p}{10^{37} \text{ ergs s}^{-1}}\right)\left(\frac{c}{a\Omega}\right)^{1/2} M_\odot \text{ yr}^{-1} , \tag{17}$$

with a the plasma injection distance from the neutron star. In this case there may be an Alfvén radius near the neutron star, but pulsar magnetic radiation pressure near the plasma injection distance pushes away that plasma before it can get near enough to the star.

If $\dot{M}$ falls below $\sim 10^{-2}$ the neutron star's Eddington limit while the neutron star's period is still $\sim 10^{-3}$ s, then equations (14), (16), and (17), make possible a relatively abrupt quenching of the neutron star's accretion. This may point to a solution of one of the problems of § I, why observed LMXBs seem to have $L_X > 10^{36}$ ergs s^{-1}. Alternatively, another mechanism (RSTE) may abruptly reduce $\dot{M}$ and the pulsar radiation then quenches it completely and permanently. However, we are now left with a millisecond pulsar with a companion whose mass $m > 10^{-2}\ M_\odot$. Why does the companion often, perhaps always, subsequently disappear?

The secondary is illuminated by the radiation emitted from an isolated $P \approx 10^{-3}$ s pulsar with a spin-down power $\sim 3 \times 10^{37}$ ergs s^{-1} lasting for $\sim 10^8$ yr (see equation [14] and § IV). There is no direct evidence, even from the almost 10^{-3} s period PSR 1937+21 and PSR 1821−24 of the form such radiation would take. The total magnetospheric voltage drop $\Omega B_s R^3 c^{-2}$ and current flow $\Omega^2 B_s R^3 c^{-1}$ are somewhat greater than those of the Crab pulsar. The whole magnetosphere of the millisecond pulsar with 5×10^8 G $< B_s < 4 \times 10^6$ G resembles the outermagnetospheres of young more slowly spinning strong field Vela and Crab pulsars. The outermagnetosphere of these pulsars has been argued to be the seat for all the observed energetic radiation and almost all of the very abundant $e^\pm$ winds from these pulsars (Cheng, Ho, and Ruderman 1986). If we take the Vela and Crab pulsars as the prototypes for what might be expected from a $P \approx 10^{-3}$ s, $B_s \approx 5 \times 10^8$ G pulsar we would expect the following.

1. *Electromagnetic radiation.*—10^3 Hz radiation with a total power of $\sim 3 \times 10^{37}$ ergs s^{-1}.
2. *X-rays.*—The Crab pulsar emits most strongly in X-rays while Vela is extremely weak in this range. PSR 1937+21 is not a known X-ray source. There is therefore no strong argument that a 10^{-3} s weak field pulsar would be a strong X-ray source.
3. *γ-rays.*—About 10^{-2} of Vela spin-down power is emitted as γ-rays with energy larger than 10^6 eV and an $\sim E^{-1}$ intensity spectrum between 1 MeV and 1 GeV. We shall assume a similar emission from the putative 10^{-3} s pulsar.

$$I_\gamma = \frac{3 \times 10^{35}}{E \times \ln 10^3} \text{ ergs s}^{-1} \text{ MeV}^{-1} . \tag{18}$$

4. *$e^\pm$ Wind.*—A 6×10^{38} ergs s^{-1} $e^\pm$ wind from the Crab pulsar seems to account for its nebula's synchrotron radiation and accelerated expansion. Copious $e^\pm$ production is expected in the Crab and Vela outermagnetosphere. Synchro-Compton acceleration to 10^{12} eV could be a consequence of the injection of this pair plasma into the strong-low frequency electromagnetic radiation of 1. We shall, therefore, simply assume that a remnant low field 10^{-3} s pulsar of an LMXB would give most of its 3×10^{37} ergs s^{-1} of spin-down power to a similar 10^{12} eV $e^\pm$ wind.

Radiation of the forms 3 and 4 above seem to be the more plausible candidates for inducing a continuing evaporation of the secondary. The estimate of equation (8) for a γ-ray induced wind applied to the γ-ray spectrum of equation (18) and the subtended secondary solid angle from the primary,

$$\psi \times \frac{1}{9}\left(\frac{m}{3M}\right)^{2/3} \approx \frac{10^{-2}}{4}\left(\frac{m}{10^{-2}\,M_\odot}\right)^{2/3} \tag{19}$$

gives

$$\dot{m}_w \approx -3 \times 10^{17}\psi f \approx 10^{15}(m/10^{-2}\,M_\odot)^{2/3} f \text{ g s}^{-1} . \tag{20}$$

A $10^{-2}\,M_\odot$ secondary would be evaporated in $\sim 7 \times 10^8$ yr. This is longer than the spin-down time of the pulsar, so that it is problematic whether pulsar γ-rays alone would be effective in removing the secondary when the isolated pulsar must be left spinning no slower than 1.5×10^{-3} s if this is to be a plausible scenario for the formation of PSR 1937+21.

A flux of 10^{12} eV $e^\pm$ would penetrate too deeply into a secondary to be efficient in inducing evaporation other than by just forming a heat source somewhat below the stellar surface. If the primary is an $e^\pm$ source of strength $<2 \times 10^{37}$ ergs s^{-1}, equation (15) for a $m \approx 10^{-2}\,M_\odot$ secondary gives $\hat{L}/\hat{L}_{\text{Eddington}} < 10^{-1}$, so that the secondary's Eddington limit is not reached in this mass regime: the induced surface temperature $T_g \approx 10^5$ K is less than 1/20 of that which might sustain very large thermal evaporation for a star with a mass to radius ($\hat{R}$) ratio $m\hat{R}^{-1} \approx 10^{21}$ g cm^{-1}. The power in a strong incident $e^\pm$ flux onto the companion may, however, be converted into a form in which it becomes much more effective in inducing an evaporative wind. Even a modest magnetic field would result in a synchrotron radiation conversion of the 10^{12} eV energy of any e^+ or e^- into a huge number of energetic photons which could greatly increase the evaporative wind resulting from the same incident power. For example, if the companion dwarf had only about the same dipole flux as that typically found in the Sun, its surface field would be $\sim 10^2$ G. A similar magnetic field would be expected from reflection of the very strong incident magnetic dipole kilohertz radiation from the pulsar. The typical synchrotron quantum energy in such a field (B) from $e^\pm$ with energy $E_\pm \approx 10^{12}$ eV is

$$\hbar\omega \approx \left(\frac{E_\pm}{mc^2}\right)^2 \frac{\hbar e B}{mc} \approx 10^6 \text{ eV} . \tag{21}$$

From equation (8), and with the angular fraction ψ defined in equation (19), the resulting MeV flux onto the stellar surface would sustain an evaporative wind from the secondary

$$\dot{m}_w \approx -\frac{10^{-19}}{4}(m/10^{-2}\,M_\odot)^{2/3} L_\pm \tag{22}$$

with $L_\pm$ the $e^\pm$ power from the pulsar. For $L_\pm \approx 2 \times 10^{37}$ ergs s^{-1} and $m \approx 10^{-2}\,M_\odot$, $|\dot{m}_w| \leq 5 \times 10^{17}$ g s^{-1}. With equation (9) the wind kinetic energy density at the stellar surface

$$\epsilon_{\text{kin}} \approx \frac{|\dot{m}_w| v_w}{8\pi\hat{R}^2} > 10^5 \text{ ergs cm}^{-3} \gg \frac{B^2}{8\pi} \approx 4 \times 10^2 \text{ ergs cm}^{-3} \tag{23}$$

so that the secondary's magnetic field would not contain the wind. With the above evaporative mass loss rate a companion star with initial $m \approx$ *several* $10^{-2}\,M_\odot$ would evaporate completely in 3×10^6 yr. This would be rapid enough to account for the apparent relatively abrupt turnoff of neutron star accretion in LMXBs discussed in § I and for observations of solitary spun-up neutron stars which did not spin-down in dying LMXBs.

Note that the estimates for the power of the pulsar-induced winds of this section assumed that the secondary fills the Roche lobe. If applied to situations where the secondary subtends only a fraction q of the projected area of its Roche lobe, all wind estimates must be reduced by this same factor.

IV. RADIATED SPIN-DOWN POWER AND SECONDARY EVAPORATION BY MAXIMALLY SPUN-UP PRIMARIES

There are two qualitatively distinct contributions to the power radiated from a spun-up neutron star and its accretion disk. When a steady state has been achieved the descent onto the neutron star surface from the inner edge of the accretion disk (which rotates slightly faster than the neutron star) gives an accretion power

$$\dot{E}_a \approx \frac{GM\dot{M}}{R} , \tag{24}$$

with R the neutron star radius. Most of $\dot{E}_a$ goes into radiation. The infall gives a neutron star spin-up torque of order

$$N_u \approx \dot{M}(GMR_A)^{1/2} \tag{25}$$

with R_A the radius of the inner edge of the Keplerian accretion disk. According to Ghosh and Lamb (1979) in a steady state there is also an equal spin-down torque from the magnetic coupling between the star and more distant parts of the disk which are rotating more slowly than the neutron star

$$N_d \approx B_s^2\left(\frac{R}{R_A}\right)^6 R_A^3 . \tag{26}$$

In the steady state, the condition $N_u = N_d$ defines R_A. The power dissipation from the spin-down torque[4] (perhaps in magnetic field stretching and reconnection) is

$$\dot{E}_d \approx N_d \Omega_{ns} \tag{27}$$

with Ω_{ns} the neutron star angular spin rate. For the spun-up neutron star steady state we then have (with an accuracy that it is expected to be better than an order of magnitude)

$$\dot{E}_d \approx \frac{R}{R_A} \dot{E}_a . \tag{28}$$

Thus, for a strong magnetic field X-ray pulsar, such as Her X-1 with $R/R_A \approx 10^{-2}$, $\dot{E}_d$ is small relative to $\dot{E}_u$. However, LMXB neutron stars are presumed to have weak B_s, which we will assume to be $B_s \approx 5 \times 10^8$ G. If $\dot{M} \approx 10^{18}$ g s^{-1}, near the neutron star's Eddington limit, $R_A \approx R$ and $\dot{E}_d \approx \dot{E}_a$. Then, in the LMXB steady state with a neutron star spun-up to a period $P \approx 10^{-3}$ s, $\dot{E}_d \approx 10^{38}$ ergs s^{-1}. If $\dot{M}$ begins to drop, $\dot{E}_a$ must follow but there can be a significant lag in the drop of $\dot{E}_d$ if the spin kinetic energy of the neutron star is large enough to maintain Ω_{ns} despite the spin-down torque (see Figs. 1 and 2). As long as the neutron star spin period remains near 10^{-3} s a large amount of spin-down power must be radiated away no matter how small the Roche-lobe–driven $|\dot{m}|$ becomes. The lower limit of this power is reached when the disk inner radius R_A grows to be beyond the light cylinder radius of the spinning neutron star $c/\Omega \approx 5 \times 10^6$ cm. Then the neutron star could radiate like an isolated millisecond pulsar (e.g., PSR 1937+21) as discussed in § III with an energy loss rate of equation (14) and a spin-down lifetime

$$\tau = \frac{E_p}{\dot{E}_p} \approx 10^8 \left(\frac{P}{10^{-3}}\right) \text{ yr.} \tag{29}$$

We note that from equation (27) for an accretion disk radius $R_A < c/\Omega$, the radiated spin-down power would be expected be even greater than that of equation (14) by a factor of order $(c/\Omega R_A)^3$. The larger spin-down energy release from the Ghosh-Lamb spin-down torque is shown in Figures 1 and 2. From equation (7) with $\xi = 1$ and $X_M \approx 10^{-3}$ (for canonical metal abundance in the secondary) the X-ray–driven evaporation rate of the secondary is of order 2×10^{16} g s^{-1}. This could speed up the evolution time of a secondary with $m \approx 3 \times 10^{-2} M_\odot$ to 10^8 yr during which the total radiated X-ray power would have remained above $\sim 10^{37}$ ergs s^{-1}. The problem, however, remains of understanding how m reached an "initial" mass of $3 \times 10^{-2} M_\odot$ before substantial spin-down of the neutron star. It is marginal whether gravitational radiation can accomplish this (but illumination of the secondary by soft X-rays and MeV γ-rays may "quickly" carry the evolution to light secondary mass; see RSTE 1989 and § V).

V. EVAPORATION OF SECONDARIES BY ACCRETION POWER FROM PRIMARIES

The composition of very light secondaries in LMXBs is not known. In some scenarios for the formation and evolution of such systems (see, e.g., van den Heuvel 1986) they originated as white dwarfs receiving mass from a secondary companion which overflows its Roche lobe because of nuclear burning of its He core. The white dwarf ultimately exceeds its Chandrasekhar limit and implodes to a neutron star. The remnant C/O core of the supergiant secondary cools to become the neutron star's degenerate companion. Gravitational radiation or the removal of angular momentum by magnetic braking (Rappaport, Verbunt, and Joss 1983) brings the secondary close enough to the neutron star that Roche lobe overflow begins again to give an X-ray bright LMXB. As discussed in RSTE (1989), when accretion in the LMXB drops by one order of magnitude below Eddington, coronal interception of this radiation will be unimportant. However, a very large cool corona may exist, which can scatter the X-rays onto the companion. Then from equation (7) with $X_M \approx 0.1$ for a strongly metallic secondary and from equation (19)

$$\dot{m}_w \approx -10^{-19} \xi L_X \text{ g s}^{-1} . \tag{30}$$

We note that the only degenerate dwarf companions in LMXBs which have been identified so far, 1820−30 (Stella, White, and Priedhorsky 1987), and 4U 1915−05 (White and Swank 1982; Smale *et al.* 1988), have a large abundance of He because they are bursters, and existing burst models rule out pure C-O ignition. However, considerations for H-He companions discussed below may be applicable to 1820−30 and 4U 1915−16. The wind velocity of equation (6) is large enough to escape the binary and thus remove angular momentum from it when the mass of the secondary is not too small. The escape velocity from the orbit of radius a should be less than the sum of v_w and the orbital velocity, or

$$v_w > \left(\frac{GM}{a}\right)^{1/2} (2^{1/2} - 1) . \tag{31}$$

For very low mass secondaries with wind velocity v_w of equation (6), a Roche lobe filling secondary at a distance a from the primary has

$$v_w = \left(\frac{GM}{a}\right)^{1/2} \left(\frac{ma}{\hat{R}M}\right)^{1/2} = \frac{(3)^{2/3}}{2^{1/2}} \left(\frac{GM}{a}\right)^{1/2} \left(\frac{m}{M}\right)^{1/3} . \tag{32}$$

[4] The relevance of spin-down torque energy loss in LMXBs is addressed in Shaham and Tavani (1986, 1987). A model of Sco X-1 based on dissipation of spin-down energy has been studied in Priedhorsky (1986).

Inequality (31) would be satisfied as long as

$$\frac{m}{M_\odot} > 2.2 \times 10^{-2}. \tag{33}$$

The angular momentum loss from the system could then drive a Roche lobe overflow rate (RSTE)

$$\dot{M} \approx \left|\frac{\dot{m}_w}{2}\right| \tag{34}$$

in the regime of equation (4). Since

$$L_X \approx \dot{M} \times 10^{20} \text{ ergs s}^{-1} \tag{35}$$

with $\dot{M}$ in g s^{-1}, the bootstrapping symbiotic relationship between equations (30) and (35) leads to an ever-growing $\dot{M}$ until the accretion X-rays associated with it reach the neutron star's own Eddington limits of 10^{18} g s^{-1} and 10^{38} ergs s^{-1}, respectively, or until matter (in the form of a corona) starts blocking the line of sight to the companion. We note that for a light H or He degenerate dwarf secondary with $X_M \approx 10^{-3}$ the right-hand side of equation (30) is reduced by a factor of 10^{-2} so that instead of pushing up to and then sustaining Eddington limit accretion onto the neutron star the steady state equilibrium bootstrapped accretion would fall to zero if there were no other source of angular momentum loss from the LMXB.

X-ray illumination of a H/He secondary by the neutron star primary and its accretion disk would then be unimportant until m falls below $\sim 10^{-3}\, M_\odot$ where that illumination may exceed the secondary's small Eddington limit. If that occurs and v_w still satisfies equation (31), i.e., it is above the value given in equation (6) (see RSTE) and if only gravitational radiation removes angular momentum from the binary its mass loss rate would evolve as shown in Figure 5. When the Roche-lobe–filling secondary's mass drops below $\sim 10^{-1}\, M_\odot$, gravitational radiation can no longer sustain near Eddington limit accretion, and accretion-powered X-ray illumination of the secondary which *may* restore that high accretion rate when m falls below $10^{-3}\, M_\odot$ (line *d* of Fig. 5) is ineffective for m between 10^{-3} and $10^{-1}\, M_\odot$. Moreover it would take well over 10^{10} yr for m to pass through that interval (Figs. 1 and 2) which, as discussed in § I, is calculated to be negotiated much more rapidly (and thus accounts for a lack of observation of it) with or without such a huge fall in the accretion-powered X-ray luminosity as that inferred from the $\dot{M}$ of Figure 5.

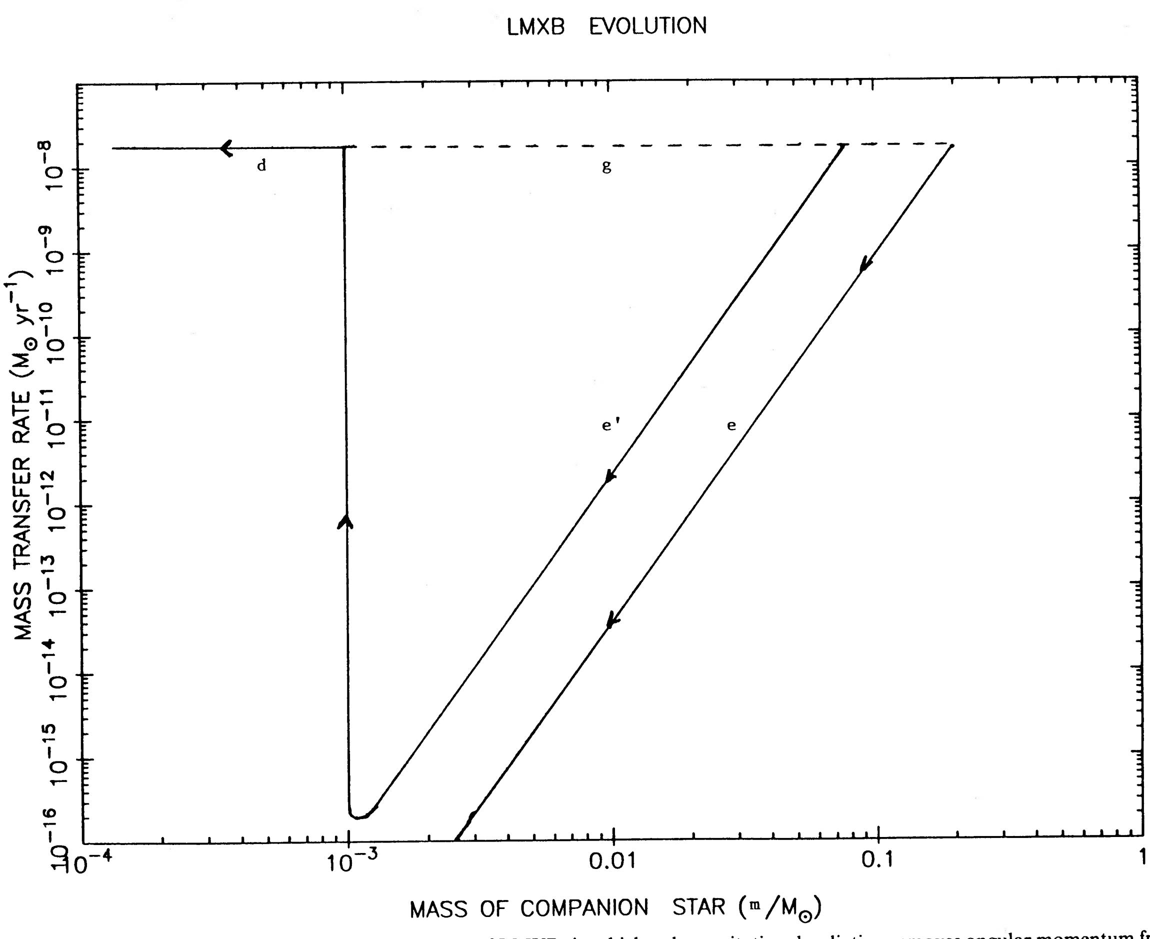

FIG. 5.—Possible evolution of H and He secondary mass loss rates of LMXBs in which only gravitational radiation removes angular momentum from the binary and super-Eddington illumination is received by the secondary when its mass drops to $10^{-3}\, M_\odot$.

The suggestion that the secondary may be tidally disrupted when m falls well below $10^{-2}\, M_\odot$ must face the problem of evolving to that low m rapidly enough (Jeffrey 1986; Ruderman and Shaham 1985). One possibility for sustaining high $\dot{M}$ and/or L_X in most of that gap (i.e., evolution along line g after only a short excursion along e or e' of Fig. 3) is secondary illumination and evaporation by an $e^{\pm}$ wind with MeV γ-rays (equation [8] and §§ IIa and IIb) which are plausible emissions from the outer magnetosphere of LMXB neutron stars (RSTE). Another possibility (§ IV) may be sustaining radiation from the primary which illuminates and evaporates the secondary by the spin-down energy release from a maximally spun-up neutron star which can remain large even when there is no longer a large $|\dot{m}|$ to give accretion-powered radiation.

For sustaining secondary evaporation by X-rays in LMXBs and even in Her X-1 (McCray *et al.* 1982; Vrtilek and Halpern 1985) a larger fraction of the total luminosity in soft (0.2–1 keV) X-rays compared to the assumed emission from Her X-1 in the model of London *et al.* (1981) would be important in equation (7). A systematic study of spectra of LMXBs shows an energy index ($I \approx E^{-\alpha}$ for $1 < E < 20$ keV) with α typically of order 1 (White and Mason 1985) compared to the small $\alpha \approx -0.05$ of Her X-1 (White, Swank, and Holt 1983). The parameter ξ in equation (7) is of order 5.

Then the evaporative mass loss from a H-He dwarf driven by soft X-rays (0.2–1 keV) is, from equations (7) and (19)

$$\dot{m}_w \approx 10^{18} L_{X,38}\ \mathrm{g\ s^{-1}}\ . \tag{36}$$

The consequences of this may be important for the evolution of LMXBs. Even if the $\dot{m}$ driven by gravitational radiation begins to decrease significantly within 10^7 yr, the dissipation of the resulting spin-down energy may maintain L_X close enough to the Eddington limit to sustain a strong evaporative wind for a long time.

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Note added in proof.—The estimate for the power of the pulsar-induced winds of § III (eq. [20] and beyond) assumed that the secondary fills the Roche lobe. If applied to the newly discovered millisecond eclipsing binary pulsar PSR 1957+20 (Fruchter, Stinebring, Taylor, *Nature*, **333**, 227 [1988]) where the secondary may subtend as little as $\sim 10^{-1}$ of the projected area of its Roche lobe, all wind estimates must be reduced by this same factor. The numerical value assumed for $L_\pm$ after equation (22), 2×10^{37} ergs $\mathrm{s^{-1}}$, is also much larger than the appropriate value for the new pulsar. If its total spin-down power is close to that of PSR 1937+214, $L_\pm$ in equation (22) should be reduced by at least a factor ~ 7; the predicted value of $\dot{m}_w$ for PSR 1957+20 is therefore well below $10^{16}\ \mathrm{g\ s^{-1}}$.

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