The Astrophysical Journal, 244:L13–L17, 1981 February 15

NEUTRON STAR EVOLUTION AND RESULTS FROM THE *EINSTEIN* X-RAY OBSERVATORY[1]

K. A. Van Riper
Department of Physics, University of Illinois at Urbana-Champaign, Urbana, IL 61801

AND

D. Q. Lamb
Harvard-Smithsonian Center for Astrophysics, 60 Garden Street, Cambridge, MA 02138
Received 1980 July 22; accepted 1980 November 5

ABSTRACT

We reexamine the evolution of neutron stars utilizing current knowledge of their structure and the best microphysics available, including general relativistic effects, improved opacities, and cooling by the emission of neutrinos from a pion condensate or from free quarks. We find that current soft X-ray observations of pulsars and young supernova remnants do not require stars with a pion condensate or free quarks.

Subject headings: stars: evolution — stars: neutron — X-rays: sources

I. INTRODUCTION

Investigations using the *Einstein* X-ray Observatory are yielding exciting results, such as the detection of unpulsed soft X-rays from the Crab and Vela pulsars (Harnden *et al.* 1979*a*, *b*) and from a source in the supernova remnant (SNR) RCW 103 (Tuohy and Garmire 1980). These also include interesting upper limits to the luminosities of nearby pulsars (Helfand, Chanan, and Novick 1980) and of any neutron stars in the young SNRs Cas A (Murray *et al.* 1979), Tycho (Gorenstein and Seward 1980), Kepler (Helfand, Chanan, and Novick 1980), and SN 1006 (Pye *et al.* 1980). Several of the upper limits lie below the luminosities obtained in earlier calculations of neutron star evolution (Tsuruta 1974; Malone 1974; see Tsuruta 1979 for a review). This has led to suggestions that neutron stars may cool rapidly via the emission of neutrinos from a pion condensate or from free quarks (cf. Brown 1977; Tsuruta 1980; Maxwell and Soyeur 1980).

With this issue in mind, we have reexamined the evolution of neutron stars. Our calculations, unlike many earlier ones (cf. Tsuruta 1979), include the effects of general relativity on energy transport within the star and, via the gravitational redshift, on the luminosity and temperature of the star observed at infinity. The first effect raises the central temperature and, thus, increases the neutrino luminosity of the star, while the second lowers the luminosity and surface temperature observed at infinity. Both therefore lead to a lower observed luminosity at a given age. We also present the first detailed calculations of neutron star evolution when cooling occurs via the emission of neutrinos from a pion condensate or from free quarks. A full description of our calculations and a more complete discussion of our results will be presented elsewhere (Lamb and Van Riper 1980).

[1] This research was supported in part by NSF grant PHY78-04404 and NASA contracts NSG7176 and NGR22-007-272.

II. CALCULATIONS

Our evolutionary calculations use the full general relativistic equations for stellar structure (Thorne 1966, 1977). We assume that (1) the temperature does not affect the hydrostatic structure of the stellar core, and (2) the core is isothermal (i.e., $e^{\phi}T$ = constant, where ϕ is the gravitational potential). Assumption (1) should be an excellent approximation after the first few minutes of evolution. In the beginning, the thermal conductivity, though large, cannot keep pace with the copious emission of neutrinos. Therefore at early times (age $\lesssim$1–10 yr) the core will deviate from isothermality (Malone 1974). These deviations will persist somewhat longer in stiff equation of state stars, because in these stars the crust, which has a smaller conductivity, contains a large fraction of the stellar mass (Ray 1979).

We compute a grid of model atmospheres, using the radiative opacities for iron from the new LASL *Astrophysical Opacity Library* (Huebner *et al.* 1977) and the conductive opacities of Flowers and Itoh (1976) and match them onto the isothermal core at a mantle density $\rho_m \sim 10^{10}$ g cm^{-3}. We denote the temperature at this boundary as T_m; in general relativity T_m is less than the central temperature, even though the core is "isothermal." We include in a qualitative way the effects of strong magnetic fields on the radiative and conductive opacities (Tsuruta *et al.* 1972) and on the density structure of the outer layers of the star (Flowers *et al.* 1977).

We treat all relevant neutrino cooling processes, including modified Urca, neutron-neutron (*n-n*) and neutron-proton (*n-p*) bremsstrahlung (Friman and Maxwell 1979), electron-ion bremsstrahlung (Soyeur and Brown 1979), and the plasmon process (Beaudet, Petrosian, and Salpeter 1967). We also consider cooling by the emission of neutrinos from a pion condensate (Maxwell *et al.* 1977) and from the β-decay of free quarks (Iwamoto 1980).

We include the effects of neutron and proton superfluidity on their respective specific heats and on the neutrino emissivities involving them (Takatsuka 1972; Malone 1974; Maxwell 1979). Here we use the most realistic superfluidity parameters (transition temperatures $T_{cr} = 1.7 \times 10^{10}$ K for $^1S_0$ neutron superfluidity, 9×10^8 K for $^3P_2$ neutron superfluidity, and 5×10^9 K for $^1S_0$ proton superfluidity).

We present results for 1.4 $M_\odot$ stars constructed with soft (Baym, Pethick, and Sutherland 1971, hereafter BPS) and stiff (Pandharipande and Smith 1975, hereafter PS; see also Pandharipande, Pines, and Smith 1976) equations of state, and for magnetic field strengths of zero and 4.4×10^{12} G (gauss).

III. RESULTS

The evolution of neutron stars can be described qualitatively by the equation $\tau = (1/L)\int C_v dT_m$, where τ is the age, C_v is the heat capacity, T_m is the interior temperature, and L is the luminosity of the star. In order to compare with observation, and to know the rate of photon cooling, we must also be able to relate the surface temperature T_s to T_m. We find $T_m = T_s + \alpha T_s^\beta$ to an excellent approximation, where α depends on the magnetic field B and on the surface gravity of the star, but β depends only on B and varies from 1.9 when $B = 0$ G to 3.9 when $B = 4.4 \times 10^{12}$ G.

a) *"Standard" Cooling Picture*

Figure 1 shows the heat capacities of both soft and stiff stars as a function of the interior temperature T_m when the star consists of ordinary nuclear matter. The deviations of the heat capacities from straight lines of slope +1 are due to superfluidity. In the soft star, most of the mass lies at densities above that for which superfluidity occurs. Thus the heat capacity of the neutrons dominates. In the stiff star, the central density is lower and a large fraction of the neutrons experience superfluidity. Below the corresponding transition temperatures, the neutron heat capacity first rises and then drops exponentially with temperature until only the contribution from the island of normal neutrons between the $^1S_0$ and $^3P_2$ superfluid regions remains. Thus for interior temperatures below 3×10^8 K, the heat capacities of the remaining normal neutrons and the electrons are comparable.

Figure 2 shows the luminosities of the soft and stiff stars as a function of T_m. The luminosities of both stars are dominated at high temperatures by neutrino emission and at low temperatures by photon emission from the stellar surface. The neutrino luminosity itself is dominated at high temperatures by the modified Urca process ($\propto T_m^8$) and at low temperatures by the less-temperature-dependent crust bremsstrahlung process ($\propto T_m^6$; Soyeur and Brown 1979). The photon luminosity curves are quite flat because the surface temperature T_s depends weakly on T_m. A strong magnetic field increases α^{-1} and β (see above), and therefore increases and flattens $L(T_m)$. In the stiff star, crust bremsstrahlung emission dominates for most of the neutrino cooling era (i.e., for $T_m \lesssim 7 \times 10^9$ K), whereas in the soft star it dominates only at lower temperatures when the total luminosity is dominated by photon emission from the stellar surface and the neutrino luminosity is unimportant. Neutron and proton superfluidity reduces the modified Urca neutrino emissivities exponentially with temperature. The modified Urca luminosity of the soft star is little affected by superfluidity since most of the stellar mass remains normal. In contrast, the modified Urca luminosity of the stiff star is reduced exponentially. As a result, the crust bremsstrahlung neutrino process takes over earlier (i.e., for $T_m \lesssim 2 \times 10^9$ K) than when superfluidity is absent but the total neutrino luminosity is not greatly affected. Inclusion of general relativistic effects in the

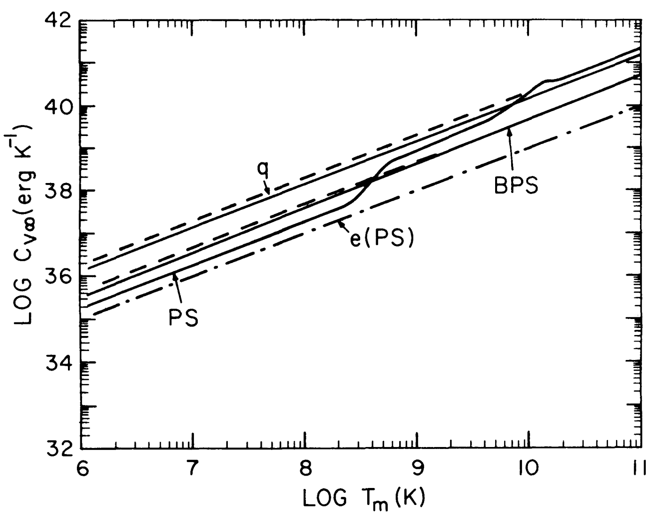

FIG. 1.—Heat capacities $C_{v\infty}$ observed at infinity as a function of interior temperature T_m. The solid curves labeled BPS and PS show the heat capacities of the soft and stiff stars with superfluidity, while the dashed lines show them in the absence of superfluidity. The curve labeled e(PS) shows the electron contribution to the heat capacity of the stiff star, while that labeled q shows the heat capacity of a star with free quarks. The heat capacity of a star with a pion condensate is assumed to be the same as that of the soft star in the absence of superfluidity.

energy transport equation enhances the modified Urca luminosity by factors of ~5 and ~2 in the soft and stiff stars, respectively, but has a negligible effect on the crust bremsstrahlung luminosities in both stars.

Figure 3 shows the resulting cooling curves for the soft and stiff stars. Our results for each star are shown as regions bounded by the cooling curves for zero magnetic field and $B = 4.4 \times 10^{12}$ G. We caution that the curves for the strong magnetic field case are uncertain owing to uncertainties in the physics involved. We assume that a strong magnetic field does not qualitatively alter the neutrino cooling processes. Then dur-

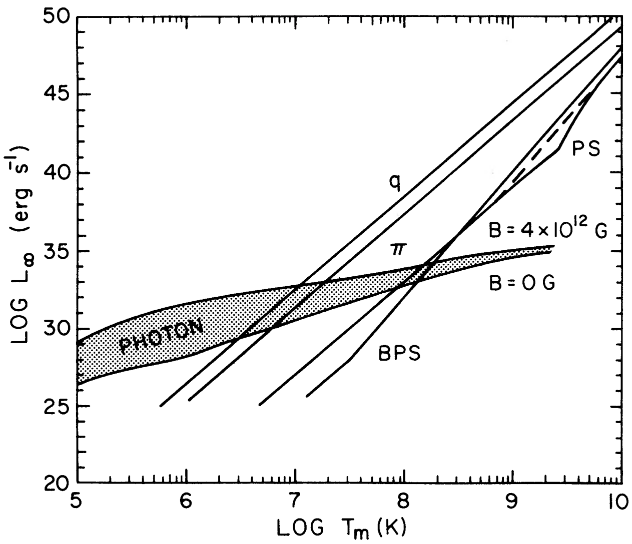

FIG. 2.—Luminosities L_∞ observed at infinity as a function of interior temperature T_m. The curves labeled BPS and PS show the neutrino luminosities of the soft and stiff stars. The curves labeled π and q show the neutrino luminosities of stars with a pion condensate and with free quarks. The curves labeled *Photon* show the photon luminosities for stars with $B = 0$ and 4.4×10^{12} G; these curves are nearly identical for all of the stars. The lightly shaded region between these two curves represents the photon luminosity curves for intermediate values of the magnetic field.

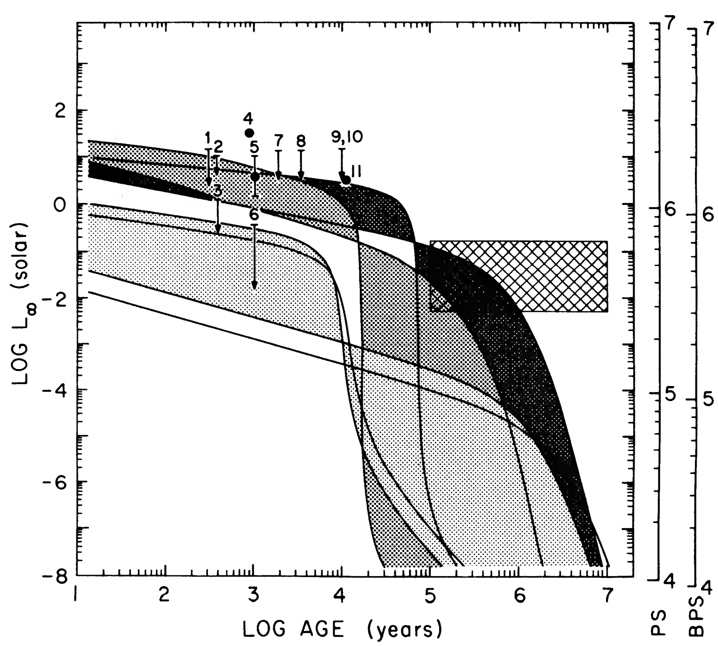

FIG. 3.—Theoretical cooling curves compared with observations. The results for each star are shown as regions bounded by the cooling curves for $B = 0$ and 4.4×10^{12} G. *Dark shading:* soft (BPS) star; *medium shading:* stiff (PS) star; *light shading:* star with a pion condensate; *no shading:* star with free quarks. Also shown are detections (*filled circles*) and upper limits (*arrows*) obtained from *Einstein* soft X-ray observations of pulsars and supernova remnants. The objects shown are (1) Cas A, (2) Kepler, (3) Tycho, (4) Crab, (5) RCW 103, (6) SN 1006, (7) RCW 86, (8) W28, (9) G350.0−18, (10) G22.7−0.2, and (11) Vela. The cross-hatched rectangle characterizes the upper limits that have been obtained for seven nearby pulsars.

ing the neutrino cooling era (age $\tau \lesssim 10^4$ yr), the interior temperatures of the nonmagnetic and magnetic stars are the same, but the photon luminosity of the magnetic star is greater because the difference between T_s and T_m is smaller. During the photon cooling era, the magnetic stars cool more rapidly because of their greater photon luminosity. The cooling curves cross when the neutrino and photon luminosities are comparable.

The slopes of the cooling curves for the soft and stiff stars differ during the neutrino cooling era. In the soft star, neutrons provide most of the heat capacity ($C_v \propto T_m$) and the modified Urca process ($\epsilon_\nu \propto T_m^8$) provides most of the neutrino luminosity. Thus $\tau \propto \int T_m dT_m / T_m^8 \propto T_m^{-6} \propto T_s^{-12}$, or $L \propto \tau^{-1/3}$, where here and below we use $T_s \propto T_m^{1/2}$ (see above). In the stiff star, neutrons and electrons provide most of the heat capacity ($C_v \propto T_m$) when $\tau \gtrsim 1000$ yr, and the bremsstrahlung process ($\epsilon_\nu \propto T_m^6$) provides most of the neutrino luminosity; thus $L \propto \tau^{-1/2}$. At earlier times, neutrons provide most of the heat capacity, which is falling exponentially because of superfluidity. This produces the curvature seen in the cooling curves for the stiff star prior to 1000 yr.

Early in the photon cooling era, both soft and stiff stars cool rapidly, since the photon luminosity $L \propto T_s^4 \propto T_m^2$ and thus $\tau \propto \int T_m dT_m / T_s^4 \propto \int dT_m / T_m$ is nearly singular. Later, $T_s = T_m$ when the infinite conductivity limit is approached in the outer layers of both stars. Then $\tau \propto \int T_m dT_m / T_s^4 \propto T_s^{-2}$ or $L \propto \tau^{-2}$.

An important feature of our results is that both soft and stiff stars cool more rapidly than in earlier calculations. Thus at $\tau = 1000$ yr, for example, we find for our soft (stiff) star a luminosity ~ 16 (40) times lower than found by Tsuruta (1979).[2] In the soft star, much of the difference is due to our inclusion of general relativistic effects (particularly the gravitational redshift), although part appears to be due to our use of new radiative and conductive opacities. In the stiff star, general relativistic effects are smaller. We find, however, that it cools somewhat faster because superfluidity markedly reduces its heat capacity but does not affect its dominant energy loss processes, i.e., neutrino crust bremsstrahlung and photon emission from the stellar surface. Nevertheless, the luminosities of the soft and stiff stars differ very little during the neutrino cooling era. Therefore current soft X-ray observations, which measure only photon flux, cannot distinguish between soft and stiff equations of state. Ultraviolet observations of old neutron stars could do so, *if* the stellar age is known and if no other mechanisms have heated the star (cf. Tsuruta 1979; Helfand, Chanan, and Novick 1980).

[2] We received the paper by Glen and Sutherland (1980) after our calculations were largely complete. Their results can be compared with ours only for the case of zero magnetic field, since we treated the effects of the field on the density structure of the outer layers of the star, whereas they did not. For zero magnetic field, our luminosities for the soft star agree (e.g., they are within a factor ~ 2 at $\tau = 1000$ yr), but our luminosities for the stiff star differ somewhat (ours is a factor ~ 13 lower at $\tau = 1000$ yr).

b) "Nonstandard" Cooling Picture

The existence of a pion condensate in neutron stars is not unlikely if the central density exceeds several times nuclear matter density ρ_0; in contrast, the existence of free quarks in neutron stars is highly speculative (see Baym and Pethick 1979). In both cases we adopt a transition density $\rho_{cr} = 2\rho_0$. This value is reasonable in the case of a pion condensate, but is optimistic in the case of free quarks. However, both the heat capacity and the neutrino emissivity of quark matter increase with increasing density (Iwamoto 1980) and are dominated by the contributions from matter at the very center of the star. Thus they are insensitive to the choice of ρ_{cr}. Note that the central density of the stiff star is insufficient for a pion condensate or free quarks to occur.

In the absence of firm knowledge of the equation of state for either pion condensed or quark matter, we have used the soft (BPS) star equation of state. This is reasonable since the existence of a pion condensed or free quark phase is expected to soften the equation of state. The heat capacities of pion condensed and quark matter are also very uncertain. For the pion condensate, we have retained the heat capacity of free neutrons, while for the quarks we use the expression given by Iwamoto (1980). In the expressions for the neutrino emissivities, we have used the parameter values in Maxwell *et al.* (1977) for the pion condensate, except we take $\theta^2 = 0.01$, and the values in Iwamoto (1980) for the quarks. We do not consider the possible effects of superfluidity. As shown in Figures 1 and 2, the heat capacity of quark matter is larger than that of pion condensed matter, mostly owing to the tripled number of particles, while the neutrino emissivity is even larger relative to that of a pion condensate, owing to its greater density dependence (Iwamoto 1980).

Figure 3 shows our results for stars with a pion condensate or with free quarks. The neutrino emissivity $\epsilon_\nu \propto T_m^6$ for both the pion condensate and the free quarks, so that the slopes of the cooling curves in the neutrino, as well as the photon, cooling eras are the same as that of the stiff star in the "standard" cooling picture. We find that stars with a pion condensate or free quarks cool markedly faster than in the "standard" cooling picture, reaching luminosities 10^3 times smaller at $\tau = 1000$ yr. With the above choice of specific heats and parameter values in the neutrino emissivities, the cooling curves are similar; however, both quantities are poorly known. Discovery of young neutron stars having $L/L_\odot \lesssim 10^{-1}$ would thus strongly favor the "nonstandard" picture, but could not distinguish between a pion condensate or free quarks.

IV. DISCUSSION

Figure 3 shows data for a number of sources that have been studied using the *Einstein* X-Ray Observatory. Only the total photon flux is measured so that different assumptions about the stellar radius lead to different values of the temperature. If the data is displayed as a plot of temperature versus age, as previous authors have done, each source requires a separate data point for every model with which it is compared (cf. Tsuruta 1979, Fig. 7). In contrast, only a single point is required for each source when the data is displayed as a plot of luminosity versus age, apart from differences introduced by convolution of the (assumed) blackbody spectrum of the star with the interstellar absorption and the detector response. These differences are much smaller than the uncertainties introduced by poorly known interstellar column densities to the sources, unless $T_\infty \ll 1 \times 10^6$ K. We conclude that plots of the luminosity observed at infinity L_∞ versus age are the most model-independent and best way to present and compare theory and current observations.

The detections we have plotted in Figure 3 are for the Crab and Vela pulsars (Harnden *et al.* 1979*a*, *b*) and for the source in the SNR RCW 103 (Tuohy and Garmire 1980). The point plotted for the Crab pulsar corresponds to the minimum of its pulse profile. The point plotted for the Vela pulsar corresponds to the maximum flux from a point source that is consistent with the data. We have also plotted upper limits in Figure 3 for any neutron stars in the young SNRs Cas A (Murray *et al.* 1979), Kepler (Helfand, Chanan, and Novick 1980), Tycho (Gorenstein and Seward 1980), and SN 1006 (Pye *et al.* 1980) and in the older SNRs RCW 86, W28, G350.0−18, and G22.7−0.2 (Helfand, Chanan, and Novick 1980). The uncertainties in the luminosities are dominated by the uncertainty in the column density to the sources. We have assumed either a factor of 10 uncertainty in the column density, or have used different measurements of it if they differ by more than this. The ages of the Kepler, Tycho, Crab, SN 1006, and RCW 86 SNRs are known from historical records; in the other cases the ages are taken from SNR blast wave models, which are uncertain. However, we have not indicated these latter uncertainties in Figure 3. We have also plotted a rectangle in Figure 3 to characterize the upper limits derived for seven nearby pulsars (Helfand, Chanan, and Novick 1980). The ages of these pulsars are unknown, but are expected to lie in the range 10^5–10^7 yr (Taylor and Manchester 1977).

Comparison of the theoretical cooling curves and the observational data shows that all of the sources lie on or above the "standard" cooling curves for either soft or stiff stars, with the possible exceptions of Tycho and SN 1006. The upper limits for these latter two SNRs are marginally inconsistent with the "standard" cooling curves and would be more so if smaller distances or less conservative estimates of the interstellar column density were adopted, *if* it is assumed that neutron stars are present in these remnants. There is, however, no evidence at present to suggest this. We conclude that current observations are entirely consistent with the "standard" cooling picture and do not require stars with a pion condensate or free quarks.

The upper limit for the older SNRs lie above the cooling curves for both soft and stiff stars; it is therefore premature to conclude that none of these SNRs contain neutron stars. Further, we note that the data points for the Crab and Vela pulsars also lie above the theoretical cooling curves. This suggests that the X-ray flux from these sources may be augmented by nonthermal radiation associated with the pulsar emission process or other heating mechanisms (see Tsuruta 1979; Helfand, Chanan, and Novick 1980). Alternatively, this could indicate higher magnetic fields or the absence of neutron superfluidity. We caution, however, that all of these inferences are based on the cooling curves for strongly magnetic stars which are at present very uncertain.

We gratefully acknowledge the warm hospitality of the Los Alamos Scientific Laboratory, the Aspen Center for Physics, and the Institute for Theoretical Physics.

REFERENCES

Baym, G., and Pethick, C. J. 1979, *Ann. Rev. Astr. Ap.*, **17**, 415.
Baym, G., Pethick, C. J., and Sutherland, P. G. 1971, *Ap. J.*, **170**, 299 (BPS).
Beaudet, G., Petrosian, V., and Salpeter, E. E. 1967, *Ap. J.*, **150**, 979.
Brown, G. E. 1977, *Comments Ap. Space Phys.*, **7**, 67.
Flowers, E. G., and Itoh, N. 1976, *Ap. J.*, **206**, 218.
Flowers, E. G., Lee, J.-F., Ruderman, M. A., Sutherland, P. G., Hillebrandt, W., and Müller, E. 1977, *Ap. J.*, **215**, 291.
Friman, B. L., and Maxwell, O. V. 1979, *Ap. J.*, **232**, 541.
Glen, G., and Sutherland, P. G. 1980, *Ap. J.*, **239**, 671.
Gorenstein, P., and Seward, F. D. 1980, private communication.
Harnden, F. R., Jr., Buehler, B., Giacconi, R., Grindlay, J., Hertz, P., Schreier, E., Seward, F. D., Tananbaum, H., and Van Speybroeck, L. 1979*a*, *Bull. AAS*, **11**, 789.
Harnden, F. R., Jr., Hertz, P., Gorenstein, P., Grindlay, J., Schreier, E., and Seward, F. D. 1979*b*, *Bull. AAS*, **11**, 424.
Helfand, D. J., Chanan, G. A., and Novick, R. 1980, *Nature*, **283**, 337.
Heubner, W. F., Merts, A. L., Magee, N. H., Jr., and Argo., M. F. 1977, *Astrophysical Opacity Library* (Rept. No. LA 6760M, Los Alamos Scientific Lab).
Iwamoto, N. 1980, *Phys. Rev. Letters*, **44**, 1637.
Lamb, D. Q., and Van Riper, K. A. 1980, in preparation.
Malone, R. C. 1974, Ph.D. thesis, Cornell University.
Maxwell, O. V. 1979, *Ap. J.*, **231**, 201.
Maxwell, O. V., Brown, G. E., Campbell, D. K., Dashen, R. F., and Manassah, J. T. 1977, *Ap. J.*, **216**, 77.
Pandharipande, V. R., Pines, D., and Smith, R. A. 1976, *Ap. J.*, **208**, 550.
Pandharipande, V. R., and Smith, R. A. 1975, *Nucl. Phys. A*, **237**, 507.
Pye, J. P., Pounds, K. A., Rolf, D. P., Seward, F. D., Smith, A., and Willingale, R. 1980, *M.N.R.A.S.*, in press.
Ray, A. 1979, Ph.D. thesis, Columbia University.
Soyeur, M., and Brown, G. E. 1979, *Nucl. Phys. A*, **324**, 464.
Takatsuka, T. 1972, *Progr. Theor. Phys.*, **48**, 1517.
Taylor, J. H., and Manchester, R. N. 1977, *Ap. J.*, **215**, 885.
Thorne, K. S. 1966, in *High Energy Astrophysics*, ed. L. Gratton (New York: Academic Press), p. 166.
———. 1977, *Ap. J.*, **212**, 825.
Tsuruta, S. 1974, in *IAU Symposium 53, Physics of Dense Matter*, ed. C. Hansen (Boston: Reidel), p. 209.
———. 1979, *Phys. Rept.*, **56**, 237.
———. 1980, in X-Ray Astronomy, Proc. Internat. School of Ap., Course 5, Erice, 1979 July 1–14.
Tsuruta, S., Canuto, V., Lodenquai, J., and Ruderman, M. A. 1972, *Ap. J.*, **176**, 739.
Tuohy, I., and Garmire, G. 1980, *Ap. J.* (*Letters*), **239**, L107.