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Free Fall onto Magnetized Neutron Stars*

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Abstract

Some compact X-ray sources show evidence of cyclotron line radiation from excited electron Landau orbits, powered by hydrogen and helium falling onto a neutron star atmosphere along the magnetic field. The slowing of the incident matter is discussed, including the spread in energy loss due to Coulomb scattering and direct nuclear reactions for disintegrating the α particles—two problems which were first solved by Stuart Butler. The α disintegrations, followed by neutron capture, lead to nuclear γ rays; the γ-ray intensity is (indirectly) coupled to the Coulomb energy loss and the cyclotron line emission.

1. Introduction

The field of X-ray astronomy did not yet exist when Stuart Butler got his Ph.D. and Stuart never worked in this field. It is nevertheless fitting to discuss one particular topic from X-ray astronomy, the accretion of matter onto the surface of a neutron star. We shall see that two phenomena on which Butler had a great influence are intertwined in this topic. These are the energy loss of a fast ion in a plasma (Butler and Buckingham 1962) and direct nuclear reactions (Butler 1957; Butler and Pearson 1963).

Solitary neutron stars commonly produce radio pulsars; observational and theoretical studies of pulsars suggest magnetic dipole fields with surface values B of the order 10^{12} G ($\equiv 10^8$ T). For some neutron stars with a close companion star there is accretion of matter from the companion onto the neutron star surface and the release of gravitational energy produces X-ray emission. The physics of the accretion process and the radiative transfer for the emission is complicated and much of the early theoretical work neglected the magnetic field. In reality the field has important effects, including the quantization of electron orbits into Landau levels with spacing

$$\hbar\omega_c = (11\cdot 6\ \mathrm{keV}) \times (B/10^{12}\ \mathrm{G})\,. \tag{1}$$

Spontaneous radiative transitions from the first excited Landau level to the ground state are quite rapid and could lead to a cyclotron emission line. A few years ago a moderately broad spectral feature at $\sim$60 keV was observed (Trümper *et al.* 1978)

* Dedicated to the memory of Professor S. T. Butler who died on 15 May 1982.

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in the X-ray source Her X-1 which has been interpreted as a cyclotron line. The implied field of $B \approx 5 \times 10^{12}$ G, slightly stronger than typical values, has an important effect on the process of energy loss and of stopping the incident matter; this process is the subject of my paper.

The incident matter presumably has 'cosmic abundance', i.e. almost 70% (by mass) of hydrogen and about 30% of helium. Let $\phi \equiv GM/Rc^2$ be the dimensionless gravitational potential at the surface of a neutron star of mass M and radius R and consider protons (and α particles) impinging along the polar field line onto the neutron star atmosphere. The maximum energy an atmospheric electron at rest can acquire in a single 'knock-on' collision with an incident proton is $E_\phi \equiv \phi m_e c^2$. An important dimensionless parameter is then

$$\alpha_\phi \equiv \frac{\phi m_e c^2}{\hbar\omega_c} = \frac{\phi}{0{\cdot}114} \frac{5 \times 10^{12}\,\mathrm{G}}{B}. \tag{2}$$

The value of ϕ depends on the precise mass of the neutron star, with values most likely between 0·04 and 0·12. It is therefore likely that α_ϕ is *slightly less than unity* for Her X-1 and other strong-field neutron stars. This inequality $\alpha_\phi < 1$ means that the higher Landau levels are not easily excited, the slowing of the incident matter by Coulomb collisions is suppressed and slowing by nuclear collisions becomes important. This has particularly interesting implications for the one-third of the incident energy carried by α particles where direct nuclear reactions such as (p, d) and (p, pn) can take place. These reactions, which Stuart Butler has elucidated so well, are important for the slowing process itself but also as a diagnostic tool: If ^{4}He(p, pn)^{3}He is an important process, the deuteron γ-ray line emitted in a subsequent np capture should be detectable by future γ-ray satellite telescopes.

The observed cyclotron line in the X-ray emission from Her X-1 carries only a few per cent of the power radiated in the X-ray continuum, mainly at lower frequencies $h\nu \sim$ 10–20 keV. A number of theoretical papers have appeared since Trümper's original observation, both on the basic physics and the applications to Her X-1. Most of the work on Her X-1 has attempted to explain both the cyclotron line and the (more powerful) continuum emission in terms of accretion onto a relatively small surface area near the magnetic poles with the full field strength B. In this paper I shall take a somewhat different point of view, following a suggestion (Colgate and Petschek 1981) that diamagnetic effects can reduce the effective magnetic field which is seen by inflowing material. I conjecture that much of the observed 'continuum emission' comes from a larger surface area with reduced field strength; I consider explicitly only infall parallel to the full magnetic field B near the polar caps but with total accretion luminosity only 5–10% of the total observed luminosity. Even for this simpler case most of the work remains to be done, so I will mainly give a plan for necessary calculations and conjectures on results.

Section 2 describes some of the important parameters of the problem and Section 3 summarizes the 'orthodox view' on the slowing of incident matter onto a strong-field neutron star. Section 4 gives my conjecture on the slowing process for hydrogen and my assertion that most of the energy is converted into cyclotron line emission. Section 5 gives a short discussion of the slowing of α particles and the emission of nuclear γ rays.

2. Some Parameters of the Problem

We have already defined one dimensionless ratio α_ϕ in equation (2). This ratio is most important for the discussions in Sections 3 and 4, although the absolute value of ϕ will be important for direct nuclear reactions (see Section 5). A second important parameter is the rate at which matter is accreted onto the neutron star surface. It is convenient to express the accretion rate per unit surface area in units of the 'Eddington limit' for Thomson scattering with cross section σ_{Th}. This 'energy flux limit', for which radiation pressure would balance gravity, is $F_0 = GMm_{\mathrm{p}}c/\sigma_{\mathrm{Th}}R^2$ for accreting hydrogen (where m_{p} is the proton mass). The incident flux of kinetic energy is $(n_{\mathrm{i}}V_{\mathrm{i}})\phi m_{\mathrm{p}}c^2$, where n_{i} and $V_{\mathrm{i}} = (2\phi c^2)^{\frac{1}{2}}$ are the density and free-fall velocity of the incident stream just before being slowed down by the neutron star atmosphere. We define a ratio β by

$$\beta \equiv \frac{n_{\mathrm{i}}}{n_0}; \qquad n_0 = \frac{c^2\phi^{\frac{1}{2}}}{2^{\frac{1}{2}}GM\sigma_{\mathrm{Th}}} = \frac{7\cdot 2\times 10^{18}}{\mathrm{cm}^3}\frac{\phi^{\frac{1}{2}}M_\odot}{M}, \tag{3a, b}$$

where n_0 is the critical incident density that would produce the Eddington limiting flux.

For spherically symmetric time-independent accretion flow (without a magnetic field) $\beta < 1$ is required. For accretion onto a magnetized neutron star the area A of the accretion column could be much less than $4\pi R^2$, the radiation could emerge from a part of the surface *different* from where the matter is flowing in, and β could exceed unity (Basko and Sunyaev 1976). For a typical X-ray pulsar (such as Her X-1) the observed luminosity $L = \beta A F_0$ is of order $0\cdot 2(4\pi R^2 F_0)$. The 'orthodox view', summarized in Section 3, ascribes all the emission (line and continuum) to the same *very small* area A over which β is very large (of order 100). In Section 4 I shall explore the unorthodox possibility that the polar cap regions with magnetic field B account for only a few per cent of the total observed continuum luminosity. Instead of choosing a value for this percentage and for the 'polar cap area' A, I will postulate that β is slightly less than unity there.

Together with ϕ, α_ϕ and β are the main input parameters, but there are several important derived parameters. One is the column density y of atmospheric matter required to stop the incident protons with kinetic energy 938ϕ MeV. I will disregard the possibility of cooperative phenomena in the scattering process (Kirk and Galloway 1981) and of plasma instabilities (Shapiro and Salpeter 1975). The basic two-body processes (nuclear plus Coulomb scattering of Landau orbitals) are understood in principle, but estimates of y still vary: The 'orthodox view' uses $y \approx 60\,\mathrm{g\,cm^{-2}}$ for $\phi \approx 0\cdot 1$, but I will argue for smaller values. For X-ray photons far from the cyclotron resonance the number of scatterings before escape is of the order $(y/y_{\mathrm{Th}})^2$, where $y_{\mathrm{Th}} = m_{\mathrm{p}}/\sigma_{\mathrm{Th}} = 0\cdot 4\,\mathrm{g\,cm^{-2}}$. It has been shown (Wasserman and Salpeter 1980; Nagel 1981) that a cyclotron line photon is shifted far enough off resonance so that the cross section is not much larger than σ_{Th} and the total number of scatterings for an escaping photon should be less than $\sim 10^4$. A photon will then escape (rather than be absorbed) accompanied by deexcitation of a Landau level [see equation (14) of Langer *et al.* (1980); hereafter referred to as LMB], unless the proton number density n_{a} in the 'stopping layer' y of the atmosphere exceeds $5\times 10^{25}\,\mathrm{cm^{-3}}$.

The number density n_a is given by $y/m_p h_a$, where h_a is the scale height of the atmosphere in the stopping layer. If the atmosphere is an essentially static one we have $h_a \sim (2kT_a/m_p c^2\phi)R$, where T_a is the mean gas kinetic temperature in the stopping layer of the atmosphere. This gives

$$n_a \sim \frac{yc^2}{2kT_a}\frac{\phi}{R} \sim \frac{y}{50\,\mathrm{g\,cm^{-2}}}\frac{\phi}{0\cdot 1}\frac{10\,\mathrm{keV}}{kT_a}\times 10^{23}\,\mathrm{cm^{-3}}. \tag{4}$$

If y is sufficiently small and β is sufficiently large, the atmosphere is not static in the sense that the momentum transfer due to the stopping of the incident matter dominates the gravitational acceleration. The ratio of these two terms, $\sim\beta(2/\phi)^{\frac{1}{2}}y_{\mathrm{Th}}/y$, is larger than unity for some of the 'orthodox' models with a large accretion rate. This is the case for the LMB model, which I shall refer to later, but not the case if $\beta \leqslant 1$. I therefore will assume equation (4) is correct in Section 4.

3. Orthodox Models for $\alpha_\phi < 1$

We first summarize the accretion process for the field-free case $\alpha_\phi = \infty$, as discussed by Zeldovich and Shakura (1969) and by Alme and Wilson (1973). The incident protons are stopped by many collisions with atmospheric electrons; the column density for stopping is

$$y \sim (m_p/m_e)(\ln \Lambda)^{-1} m_p/\{\pi(e^2/m_e c^2)^2\phi^{-2}\}. \tag{5}$$

The term in braces is a Coulomb cross section for large-angle scattering, $\ln \Lambda$ (~ 5 or 10) is an enhancement factor for small-angle scattering and the factor m_p/m_e is the number of large-angle scatterings which would be required for an incident proton to give up its energy to electrons. The density in the stopping layer is much too low ($n_a \sim 10^{22}\,\mathrm{cm^{-3}}$) for Bremsstrahlung to be important there, so matter must be slowed and compressed further in its flow downwards before photons are created by thermal Bremsstrahlung with $kT \sim 1$ keV. Although no photons are created in the stopping layer, the matter (temperature $kT_a \sim 20$ keV) gives up much of its energy to the 'cooler' photons by Comptonization.

The presence of a strong magnetic field parallel to the accretion column has a number of different effects: The radiative transport is influenced by the opacity coefficients which depend strongly on photon frequency and on direction (Meszaros and Ventura 1978; Yahel 1980; Nagel 1981). The asymmetries allow the possibility of (but do not require) values of β larger than unity. If α_ϕ is larger than unity, an incident proton can excite an atmospheric electron into an excited Landau level, which decays radiatively very rapidly. Thus, unlike the field-free case, there *is* a way to produce new photons instead of merely scattering them. For $\alpha_\phi < 1$ the electron–proton scattering is altered drastically, especially if one neglects the temperature of the electrons entirely: The electrons cannot be excited to higher Landau levels and the equivalent of small-angle scattering (which normally leads to the Coulomb logarithmic factor $\ln \Lambda$) is suppressed. In particular, one finds that the Coulomb scattering cross section is reduced *very drastically* if the incident proton is travelling almost (or exactly) parallel to the magnetic field.

For the slowing of the incident protons (which carry most of the inflowing kinetic energy) most of the calculations to date, as well as my conjectures in the next section, assume the protons impinge exactly along the magnetic field and neglect cooperative effects. These calculations (see LMB and references therein) also omit the electron temperature in the 'first round' (slowing) of the calculation and then derive the temperature in the 'second round' (heating). If $\alpha_\phi < 1$, Coulomb collisions are almost powerless to initiate the slowing process and *nuclear* proton–proton collisions are invoked instead. The column density y for slowing and stopping the incident flow, determined by the nuclear cross section, is then $y \sim 60\,\mathrm{g\,cm^{-2}}$, at least a factor of 10 larger than the (Coulomb scattering) value in the field-free case. Once an incident proton has suffered one nuclear collision, it has lost energy and is travelling at a considerable angle to the magnetic field; in this circumstance electron–proton Coulomb collisions are quite efficient in stopping the proton and heating the electrons. In this model, excitation of higher Landau levels, and the subsequent emission of cyclotron line radiation, is only a secondary phenomenon initiated by electrons in the 'far tail' of the thermal distribution.

4. My Conjectures for $\frac{1}{4} < \alpha_\phi < 1$

Fast Proton Effects

For typical neutron star masses, and for the (relatively large) magnetic field B for Her X-1, the parameter α_ϕ in equation (2) is likely to be less than unity, but *not much less*. In particular, I will assume that $\alpha_\phi > \frac{1}{4}$, so that the incident proton velocity is more than *half* the threshold value of the relative velocity between an electron and proton for exciting the first Landau level. This inequality leads to my conjecture that the thermal velocity distribution of the atmospheric electrons *cannot* be neglected in the stopping calculation for the incident protons, but is intimately connected with the slowing process. This process is now quite involved and I will consider only cases which avoid other complications: I assume that β in equation (3a) is small, so that radiation pressure can be neglected and the atmosphere in the stopping layer can be treated as static. The mean density n_a in the stopping layer is then given by equation (4) and is sufficiently low so that collisional deexcitation of Landau levels is unimportant. Any cyclotron line photon produced in the stopping layer may scatter often but will not be absorbed, so that it eventually escapes. In reality these photon–electron scatterings can interchange energy between radiation and matter but I will neglect this complication, i.e. it is assumed that every excitation of a first Landau level leads to a radiative energy loss of $\hbar\omega_c$.

We consider a, as yet unspecified, velocity distribution $f(V_e)$ for the atmospheric electrons (of number density n_a) in the stopping layer. In analogy with equation (2) we define a kinetic energy parameter

$$\alpha_e = \tfrac{1}{2}m_e V_e^2/\hbar\omega_c. \tag{6}$$

At the moment the interaction of the electrons with the thermal protons is neglected, although we shall see that it is in fact important for determining $f(V_e)$. We consider only collisions with the fast incident protons. As mentioned (see also Pavlov and Yakovlev 1976) elastic collisions without Landau excitation have a very *small* cross section. However, using a fast incident proton and an electron moving upwards with kinetic energy

$$\alpha_e > \alpha_{e0} = (1-\alpha_\phi^{\frac{1}{2}})^2, \tag{7}$$

a Landau excitation is possible. There are two possible electron energies after the excitation,

$$\alpha_e' = [\alpha_\phi^{\frac{1}{2}} \pm \{(\alpha_e^{\frac{1}{2}} + \alpha_\phi^{\frac{1}{2}})^2 - 1\}^{\frac{1}{2}}]^2, \tag{8}$$

and the process corresponding to the minus sign has quite a *large* cross section, larger than $\pi(e^2/m_e V_e^2)^2$. For an electron initially satisfying equation (7) and interacting only with fast protons with the same energy parameter α_ϕ, we then have a chain of events which I will illustrate with one example:

We assume $\alpha_\phi = 0{\cdot}5$, so that $\alpha_{e0} = 0{\cdot}086$, and start an electron travelling upwards with $\alpha_e = 0{\cdot}087$. The first interaction with a fast incident proton releases a cyclotron line photon and gives the electron a downward kinetic energy of $\alpha_e' = 0{\cdot}41$ or $0{\cdot}59$. Although appreciable energy exchange between electrons and thermal protons is slow, elastic scatterings are fairly rapid and the electron is soon travelling upwards with almost the same value of α_e'. A second Landau excitation with a fast proton is then possible, releasing a second cyclotron photon and giving the electron a kinetic energy parameter $\alpha_e'' = 0{\cdot}04$ or $0{\cdot}14$ or, with a much smaller probability, $2{\cdot}6$ or $3{\cdot}2$. For the less likely larger values, Landau excitations in collisions with thermal atmospheric protons follow rapidly and decrease the kinetic energy of the electron. For the case with $\alpha_e'' = 0{\cdot}04$, no further Landau excitations are possible; for the other cases further collisions take place with more cyclotron photons emitted, but in each case *sooner or later the kinetic energy parameter* α_e *becomes less than* $0{\cdot}086$.

The last statement can be generalized: For an electron starting with any value of α_e *larger* than α_{e0}, after two or more interactions with fast protons the electron ends up with a value of α_e *less* than α_{e0}. The fast protons give up energy to cyclotron photons (at least $2\hbar\omega_c$, in many cases more) and slow down, but the electrons are essentially 'cooled' and not heated. Numerically, however, the 'cooling' is quite small compared with the radiative energy loss; for example, for the case with $\alpha_e'' = 0{\cdot}04$ the electron looses an energy $0{\cdot}047\,\hbar\omega_c$, compared with $2\hbar\omega_c$ in radiation.

To maintain a steady state, the collisions of the electrons with thermal protons (which we have neglected so far) must provide some heating for the electrons and these protons in turn must be heated by *nuclear* collisions with a few of the incident fast protons. This heating will maintain some fraction f_0 of the electron velocity distribution at velocities satisfying equation (7). The column density y in the stopping layer is then of the order y_0/f_0, where $y_0 \lesssim 5\ \mathrm{g\,cm^{-2}}$ is the column density appropriate if *all* the electrons had $\alpha_e > \alpha_{e0}$.

Thermal Protons as Intermediaries

We now have the curious complication that the nuclear collisions and the Coulomb scatterings for the fast and for the thermal protons all become coupled: The nuclear collisions have to take some energy out of the incident protons and then heat the ambient electrons sufficiently so that the heated electrons can interact with the fast protons; this process emits cyclotron photons, slows the protons and cools the electrons a little. Unlike in the 'orthodox' model, the column density y of the stopping layer will be only a small fraction of the value required for *all* incident protons to undergo a nuclear collision, since the electrons have to be given only a small fraction of the energy to be lost by the incident stream. The p–p differential scattering cross sections are known (Hess 1958) and, in a typical case, one of the two protons ends up with about one-third of the incident energy, moving at a large angle to the magnetic field; this proton can give up its energy to the ambient electrons quite rapidly.

Calculation of the velocity distribution of the ambient thermal electrons and protons for a steady state will have to be done numerically, but one can already make some qualitative estimates: Since I am postulating a small value of β, and expect to find a small value of y, the density n_a in the stopping layer will be appreciably smaller than in the LMB model (for which numerical results are already available). The thermal protons are heated by nuclear collisions with fast protons of density n_i and cooled by Coulomb collisions with thermal electrons of density n_a. Since n_a/n_i is now larger, I expect the proton temperature will adjust itself to some value larger than in the model by LMB, possibly $kT_{\text{proton}} \sim 50$ keV. For the electron temperature and the fraction f_0 of electrons with $\alpha_e > \alpha_{e0}$ I argue as follows.

The energy input into the electrons comes from nuclear heating (with thermal protons as intermediaries) just as in the LMB model. The cooling of the electrons in that model came from the tail of the thermal distribution ($\alpha_e > 1$) and the mean electron energy was of order 10 keV, which corresponds to $\alpha_e \sim 0{\cdot}2$, considerably larger than α_{e0} in equation (7). In our proposed model the electron energy loss will therefore come mainly from the new effect of collisions near α_{e0} with fast protons; the electron temperature will be lower than in the LMB model, but f_0 will be quite appreciable. The precise value of f_0 will depend on the 'cooling effect' of the fast protons, which in turn depends on the spread in energy of these protons at any given level. This spread, which Stuart Butler calculated so convincingly for field-free Coulomb collisions in his pioneering paper (Butler and Buckingham 1962), will have to be recalculated: The spread should come out much smaller than in Butler's case, because a slightly faster proton can interact with more electrons and will lose energy faster.

My conjectures lead to smaller density n_a, smaller column density y and more efficient Landau excitations than in previous models. Important consequences are then that almost *all* of the incident energy will flow into cyclotron line photons, collisional deexcitation is unimportant and essentially all of the line radiation can escape. This result in turn is the reason why I conjectured that only a small fraction of the total accretion flows through the polar cap region—whatever flows through there should all be converted to line radiation, but observationally the line carries only a small fraction of the energy of the continuum!

5. Direct Nuclear Reactions and Gamma-ray Diagnostic

Can the kinetic energy of the matter incident on a neutron star surface, 938ϕ MeV per nucleon, be used as a diagnostic tool for estimating ϕ? For the rare case, such as Her X-1, where the magnetic field strength B is known, one might be able to infer ϕ from the ratio α_ϕ and its effect on the X-ray spectrum. For the majority of cases, where B is not known, one might be able to use nuclear physics indirectly to estimate the incident kinetic energy and the γ-ray line spectroscopy may be more direct. For individual protons the nuclear cross sections scale approximately as ϕ^{-1}, compared with ϕ^{-2} for Coulomb cross sections, but it is not clear how to utilize this difference for measuring ϕ. However, one-third of the incident matter is in the form of ^{4}He, so that γ-ray telescopes—plus Butler's theory of direct nuclear reactions—may provide some clues:

For an incident α particle a nuclear collision need not be elastic but could lead to a nuclear disintegration and the release of a free neutron. The released neutrons could be radiatively captured by a free proton or by a ^{3}He nucleus produced in an α-particle disintegration. The emitted γ-ray line radiation, if detected from the forthcoming orbiting γ-ray observatory, would not only indicate the proportion of different nuclear captures but also register a frequency shift. If produced well into the stopping layer, where the flow speed is much smaller than the free-fall velocity, this shift would be mainly the gravitational potential redshift and its measurement could give ϕ fairly directly. If any radiative captures took place in the fast incident stream just above the stopping layer, the redshift would be even larger; this would require the ejection of some neutrons travelling *upwards* from an α disintegration with sufficient energy.

One needs to determine the rates for the various α-particle disintegrations and that is where the theory comes in: There is some experimental data for protons of 40 MeV (Eisberg 1956) and of 181 MeV (Tyrén *et al.* 1957) impinging on α particles, but history seems to have passed by the intermediate energy range. However, the two available experiments show that the theory of direct nuclear reactions, elucidated so clearly by Butler (1957) and Butler and Pearson (1963), works very reliably. The differential cross sections for p–p and for p–n scattering are known accurately over a wide range (Hess 1958) and one should be able to calculate the breakup cross sections for an incident α particle colliding with an atmospheric proton at a kinetic energy $E \sim 30$–150 MeV per nucleon. At least at the lower end of the possible energy range, the most interesting two-body process for our purposes is the peak near 180° scattering angle in the n–p collision. This process essentially puts the incident proton at rest relative to the centre of mass of the α particle and gives an energy close to E_0 to one neutron. For $E_0 \gtrsim 40$ MeV, with the α-disintegration energy only ~ 22 MeV, the neutron can easily escape and $p + {}^4He \rightarrow p + n + {}^3He$ is a likely result.

Whether the resulting ^{3}He nucleus is slowed by Coulomb collisions plus cyclotron line emission and survives, or is itself disintegrated in nuclear collisions with protons, depends somewhat on whether my conjectures on a small column density y are correct or not. This will be a particularly difficult calculation with the spread in Coulomb energy loss and direct nuclear reactions intertwined—the tragedy of losing Stuart Butler will be felt on the scientific as well as the personal side!

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References

Alme, M. L., and Wilson, J. R. (1973). *Astrophys. J.* **186**, 1015.
Basko, M. M., and Sunyaev, R. A. (1976). *Mon. Not. R. Astron. Soc.* **175**, 395.
Butler, S. T. (1957). *Phys. Rev.* **106**, 272.
Butler, S. T., and Buckingham, M. J. (1962). *Phys. Rev.* **126**, 1.
Butler, S. T., and Pearson, C. A. (1963). *Phys. Rev.* **129**, 836.

Colgate, S. A., and Petschek, A. G. (1981). *Astrophys. J.* **248**, 771.
Eisberg, R. M. (1956). *Phys. Rev.* **102**, 1104.
Hess, W. (1958). *Rev. Mod. Phys.* **30**, 368.
Kirk, J. R., and Galloway, J. J. (1981). *Mon. Not. R. Astron. Soc.* **195**, 45P.
Langer, S. H., McCray, R., and Baan, W. A. (1980). *Astrophys. J.* **238**, 731.
Meszaros, P., and Ventura, J. (1978). *Phys. Rev. Lett.* **41**, 1544.
Nagel, W. (1981). *Astrophys. J.* **251**, 278.
Pavlov, G. G., and Yakovlev, Yu. A. (1976). *JETP Lett.* **43**, 389.
Shapiro, S. L., and Salpeter, E. E. (1975). *Astrophys. J.* **198**, 671.
Trümper, J., *et al.* (1978). *Astrophys. J.* **219**, L105.
Tyrén, H., Tibell, G., and Maris, T. (1957). *Nucl. Phys.* **4**, 277.
Wasserman, I., and Salpeter, E. E. (1980). *Astrophys. J.* **241**, 1107.
Yahel, R. Z. (1980). *Astron. Astrophys.* **90**, 26.
Zeldovich, Ya. B., and Shakura, N. I. (1969). *Sov. Astron.* **13**, 175.

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