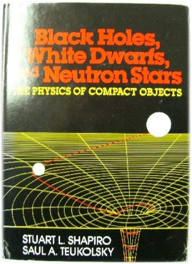
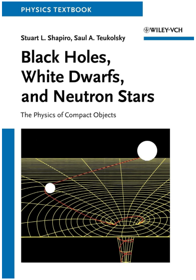
Black Holes, White Dwarfs, and Neutron Stars: The Physics of Compact Objects

Stuart Shapiro and Saul Teukolsky

ISGRG Seminar March 5, 2025





COURSE ANNOUNCEMENT

Astronomy 511: High Energy Astrophysics

S. L. Shapiro and F. Pacini. Two credit hours. (Spring semester).

This course will consist of two series of lectures on topics of current special interest in astrophysics. One series will examine systematically the physics of compact objects, i.e., white dwarfs, neutron stars, and black holes. Topics to be discussed include the formation of compact objects, equilibrium configurations, equations of state, mass limits, stability criteria, and the influence of rotation and magnetic fields. Physical processes occurring in the vicinity of compact objects will be examined, including high temperature radiation processes, pulsar emission mechanisms, mass flow in binary systems and models of spherical and disk accretion. The observations and interpretations of the compact X-ray sources (e.g., Cyg X-1 and Her X-1) and gamma-ray bursts will be discussed. (S. L. Shapiro)

The other series of lectures will examine physical conditions in extragalactic radiosources. New observational and theoretical material dealing with both extended (e.g., Cen A) and compact (e.g., 3C120) radiosources will be reviewed. Topics will include the energy and confinement problems, adiabatic losses, variability of compact components, and a critique of proposed models. Additional material on pulsars, supernovae remnants and cosmic rays will be presented. (F. Pacini)

Organization meeting will take place on Monday, January 27, 1975, Space Sciences Building Room 105 at 2:00 p.m. For further details contact S. Shapiro in Room 426 Space Sciences Building (6-4936).

THE PHYSICS OF COMPACT OBJECTS

Stuart L. Shapiro

Notes prepared for:
Astronomy 511, High Energy Astrophysics
Spring Semester
1975

Astronomy 511: High Energy Astrophysics

Instructors: Stuart L. Shapiro and Franco Pacini

Hours: 2 hours/week (to be arranged at organizational meeting)

Prerequisites: Strong background in Physics and Mathematics

Course Outline (Tentative)

A. Physics of Compact Objects (S. Shapiro)

I. Star Deaths and the Formation of Compact Objects

(i.e. white dwarfs, neutron stars, and black holes).

II. White Dwarfs

- (a) classical equilibrium configurations and polytropes
- (b) equation of state for $10^7 \text{ g cm}^{-3} < \rho < 4\times10^{12} \text{ g cm}^{-3}$.
  - (1) electron degeneracy
  - (2) electrostatic interactions
  - (3) inverse β-decay
  - (4) neutron drip
- (c) mass limits
- (d) cooling of white dwarfs
- (e) rotating and magnetic white dwarfs
- (f) comparison of theory with observations

III. Neutron Stars

- (a) relativistic equilibrium equations and analytic solutions
- (b) equation of state for $\rho > 4\times10^{12} \text{ g cm}^{-3}$
  - (1) Harrison-Wheeler equation of state
  - (2) ideal degenerate neutron gas (Oppenheimer-Volkov (1938) analysis)
  - (3) problems at high density ($\rho > 10^{14} \text{ g cm}^{-3}$)

        - (4) relativistic restrictions on the equation of state
    - (c) upper and lower mass limits
    - (d) stability criteria
    - (e) pulsars

IV. <u>Black Holes</u>

    - (a) gravitational collapse
    - (b) basic properties of the Kerr metric
        - (1) horizons and surfaces of infinite redshift
        - (2) radial trajectories and circular orbits -- the innermost stable orbit
        - (3) photon capture

V. <u>Accretion onto Compact Objects</u>

    - (a) free particle accretion
    - (b) fluid accretion
        - (1) spherical accretion onto Kerr black holes: dynamical flow and radiation spectrum
            - (a) accretion in HI and HII regions
            - (b) magnetic effects
            - (c) radiation mechanisms at high temperatures
        - (2) spherical accretion onto neutron stars
            - (a) collisional and collisionless-shock models
            - (b) the Eddington limit
            - (c) radiative transfer of X-ray photons
        - (3) disk accretion onto black holes
            - (a) the standard disk model
            - (b) the flux-radius relation
            - (c) polarization of emitted photons

- (d) thermal and dynamical instabilities
- (c) binary X-ray sources and the Uhuru observations
  - (1) Her X-1 -- a rotating magnetic neutron star
  - (2) Cyg X-1 -- a black hole
- (d) cosmic gamma-ray bursts: theories and observations
- (e) supermassive black holes
  - (1) the timescale-luminosity diagram for rapidly varying nonthermal sources (e.g. quasars)
  - (2) star clusters around massive black holes

Useful References: (all on reserve in Clark Library)

*1. Relativistic Astrophysics, Zel'dovich, Y.B. and Novikov, I.D. (U. of Chicago).

2. Gravitation Theory and Gravitational Collapse, Harrison, B., Thorne, K.S., Wakano, M., and Wheeler, J.A. (U. of Chicago).

3. Black Holes, Les Houches 1972, Ed. DeWitt and DeWitt (Gordon and Breach).

4. Gravitation and Cosmology, Weinberg, S. (Wiley).

5. Stellar Evolution, Chiu and Muriel, Ed. (MIT).

6. Principles of Stellar Evolution and Nuclear Synthesis, Clayton, D. (McGraw-Hill).

*Most comprehensive book for this course.

Also see recent review articles in Annual Review of Astronomy and Astrophysics, e.g.

(a) Ostriker, J.P., "Recent Developments in the Theory of Degenerate Dwarfs," 9, 353 (1971).

(b) Canuto, V., "Equation of State at Ultrahigh Densities," Part I., 12, 167 (1974).

(c) Blumenthal, G.R. and Tucker, W.H. "Compact X-Ray Sources," 12, 23 (1974).

B. Extragalactic Radio Sources (F. Pacini)

I. Basic Physical Conditions

- (a) extended sources (e.g., Cen A)
- (b) compact sources (e.g., 3 c 120)
- (c) energy and confinement problems
- (d) adiabatic losses
- (e) variability of compact components
- (f) comparison of theory with observations

II. Supernovae Remnants

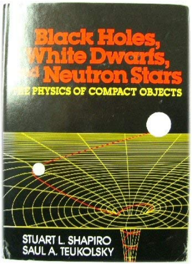
III. Cosmic Rays

IV. Pulsars

Black Holes, White Dwarfs, and Neutron Stars: The Physics of Compact Objects

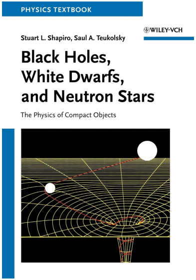
Stuart Shapiro and Saul Teukolsky

ISGRG Seminar March 5, 2025



Black Holes,
White Dwarfs,
d Neutron Stars
E PHYSICS OF COMPACT OBJECTS

STUART L. SHAPIRO
SAUL A. TEUKOLSKY



PHYSICS TEXTBOOK

WILEY-VCH

Stuart L. Shapiro, Saul A. Teukolsky

Black Holes,
White Dwarfs,
and Neutron Stars

The Physics of Compact Objects

Floyd R. Newman
Laboratory of Nuclear Studies
Cornell University
Newman Lab. Cornell Univ.
Ithaca, New York 14853
607-256- 4397

August 14, 1981

Professor Stuart Shapiro
Center for Radiophysics and Space Research
Space Sciences Building
Campus

Dear Stuart:

I shall be glad to read your Chapters 8, 9, and 18 and, at my leisure, give you comments on these.

Yours sincerely,

Hans

Hans A. Bethe

HAB:vhr

Ch. 8 §4 end (p. 270). Good discussion. The $Z \simeq 40$ is correct.

272 new result (3-body forces). Could say E near right, $\partial E/\partial \rho$ not.

(6.9) b/R, not b/r.

(6.16) is nice, how about a figure?

(6.18) $n_0 = 0.16$ much better, perhaps even less.

(6.20) OK. Ref. Youngblood '77, '78, Blaizot '76.
But previous K rather 300 than 140.

(6.22) S seems too low, would make $W = -16 + 7.5 = -8.5$
for pure neutron matter. Factor 4?

Last ¶ of 6 is OK.

Next § should be § .6 a, or something

p. 286. New Pandha & Lagaris (?)

? → 288 $g^2/\hbar c$ in (7.1) is << 10; abt. 0.08 for 1π exchange, perhaps 1 for 2π etc.

[No! $g^2/\hbar c = 15$ OPE
but $f^2/\hbar c = (g^2/\hbar c)\left(\frac{m_\pi}{2M_N}\right)^2 = 0.08$

(7.2) why g rather than g^2?

289-90: Error is not exponentially small.

p. 302 Mention Pandha.

303 BBG is not expansion in $g^2/\hbar c$, but in $\kappa = n r_c^3$
Last ¶ of Sec. 10 superseded.

304 bot. Main attraction ~~has~~ is due to 2-π exchange.

305 Pandha & ~~Lagas~~ Friedman recently got a still harder, & better founded eq. of st.

314. Is Au (1976) reliable? At higher ρ, probly much less reduction.

317, Condensation usually at finite $\vec{k}$, interaction?

318 What if particles tunnel thru potential?

318/9 Correct

322 end of Sec: Very good analysis!

326 Correct, but mention at least one good calc., such as Chapline. Also that at transition, ρ decreases sharply.

The mean field theories, esp. Walecka, are treated too favorably. It should be pointed out that short-range correlations are left out.

Fig. 8.5b: I advise against putting both on one graph. Already too confusing.

Phys. Rev. D. $\lambda = 400$

Ch. 9

Fig. 9,1 Should include Pandha–Friedman
TI no longer believed.

p. 345: Both TI and MF are unlikely. In other eq o st's, $\rho_c >> 2\rho_c$,
But 10^{15} is a good limit. ¶
Trans. to quark matter cannot be smooth but must be 1st order.
Quark stars ~~exts~~ very low mass stars. Their outside must be neutron
3rd branch very remote.

346 top: $\rho < 2\rho_{nuc}$ too much emphasized. Pion condensation is likely.

§2 ¶1. Very good.

350.9 "at least factor 2" probably wrong, Friedman & Pandha

352 (3.3) $\rho_0 = 4.6 \cdot 10^{14}$ is very low

356 (3.19) $\frac{M}{R} \leq .405$ probably means no quark stars.

Sec. 3 very useful.

358. Dropping causality seems very severe! ~~see 35~~
"Not proven" p. 359.1?

Fig. 9.5 ~~What are~~ The two lines, Rappaport vs. Baldo et al., are hard to distinguish.

792 (5.8) is $Q = m_n - m_p$? <u>18</u>, 3

793-4 ~~Where do you get $3 \cdot 10^{11}$ in (5.10)? Wouldn't it be better to give (5.10) at the end of calc.?~~ ~~But~~ I agree with the calc., <u>except</u> (5.15) which is only true for free proton capture. For capture by nuclei,

$$E_\nu \lessapprox \Delta = \mu_e - \hat{\mu} \qquad (A)$$

Our paper BBAL is better than the two you quoted, and gives $\rho_{trap} \approx 5 \cdot 10^{11}$. (A), rather than down-scattering, should be quoted.

795.~~6: Shouldn't it be Y_ℓ rather than Y_e?~~

.5 $\rho_{nucl} \sim 10^{14}$ is very rough.

797.1: Prior to neutrino trapping, $\Delta s/k = 0.2 - 0.5$, $\ll 1$. Capture by protons makes it even less.

.7 dominate for $\rho \gtrsim \rho_{drip}$

800.8 neutrino number

801 (6.15) nice formula!

802.5-7: Brown et al. take into account Fuller, & are best so far. Note their number yields ~~Y_f~~ Y_{ei}

$$Y_{ei} - Y_{ef} = 0.06 - 0.07$$

← no we find $Y_{ef} \approx 0.07$ we <u>don't</u> find $\Delta Y \approx 0.07$; we are of course very approx.

Emphasize agreement!

803.2: Free proton becomes important due to Fuller effect. Higher initial entropy not necessary.

a 18, 4

804.4 eq. (6.19) where is $E'_{f,nuc}$ explained? should be referred to. Why Exerc. 18.1?

804 bot. good.

~~Why T_{nuc}, why not just T?~~

805.9 – 6.0 Agree. is especially necessary

6.3 Smear out pairing etc.: more valid at $T \neq 0$.

Last sent.: worse at higher T. ¶ should be clarified.

807 top fine, Exerc. also

808.6 I' very

.7 why < 0.3?

809.2 0.30 no longer valid; say ~~0.34 –~~ 0.34 – 0.37.

.7 not much uncertainty near ρ_{nuc}.

810.1 Yahil has improved on Goldreich & W. $M_{hc} \approx 1.1 - 1.2\, M_\odot$

.8 Quote Wilson 19~~78~~ 80

Below (7.3) α is not the pressure deficit, but the pr. ratio.

811.9 OK, but much more could be said.

Ex. 18.16 $E = \frac{1}{2} m_B u_s^2 \geq \frac{3}{2} kT$, so kT much less.

812.9 : Neutrino opacity in outer layers << inner opacity.

813.1 : get Schramm – Arnett ref.

(7.7) Arnett gets up to $5 \cdot 10^{53}$ erg s^{-1}

814 main ¶ Generally agree. But point out flaws in hydro calculations. On non-symmetry, quote Weaver,/Wver!

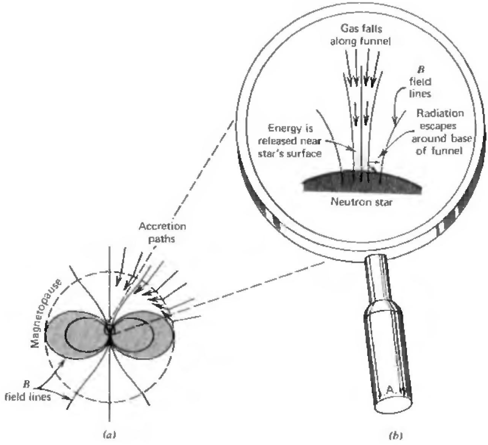


Figure 13.3 (*a*) Schematic dipole magnetosphere around a neutron star that is accreting material. Infalling gas is excluded from the toroidal region whose cross section is *shaded*. (*b*) Enlargement of the base of an accretion funnel, near a magnetic pole of the neutron star. [After Davidson and Ostriker (1973). Reprinted courtesy of the authors and *The Astrophysical Journal*, published by the University of Chicago Press; © 1973 The American Astronomical Society.]

neutron star by the accreting matter, as we will discuss in Section 15.2. In fact, the data provide further evidence in support of neutron stars in binary X-ray pulsars as opposed to white dwarfs.

(b) Orbits and Masses

Measurements of the pulse arrival times from X-ray pulsars have been employed very successfully to determine the orbits of several of the systems. In fact, there are six sources for which sufficient data—X-ray and optical—exist to estimate the masses of the compact star: Her X-1, Cen X-3, SMC X-1, LMC X-4, 4U 0900 – 40, and 4U 1538 – 52. The method was discussed in Section 9.4 and the results summarized in Figure 9.6.