Cambridge University Press 978-1-107-01657-6 - Stellar Evolution Physics: Advanced Evolution of Single Stars: Volume 2 Icko Iben Index More information

## Index

Abe, R., 1431 Abraham, M., & Becker, R., 973 acoustical pulsations of TPAGB stars such as Mira, 1393-1397 role in mass loss, 1395-1397 Adams, J. B., Ruderman, M. A., & Woo, C. H., 1052 adiabatic temperature-pressure gradient  $V_{ad}$  when pressure sources are a perfect gas plus black-body radiation, 1276-1277 AGB (asymptotic giant branch) star, a luminous red giant or supergiant giant of low to intermediate mass with an electron-degenerate core composed of C and O or of O and Ne, 1166-1218, 1260-1290, 1393, 1397-1399 see asymptotic giant branch age of Galactic disk, 1464-1469 Ajzenberg-Selove, F., 1009-1010 Ajzenberg-Selove, F., & Lauritsen, T., 1009 Allen, C. W., 927 Aller, J. S. & Chapman, S., 929-930  $\alpha$ -neutron ( $\alpha$ , n) reactions on C13 and on Ne22 are the major sources of neutrons for s-process nucleosynthesis, 1072, 1214-1218, 1291-1338, 1353, 1359 Angulo, C., Arnould, M., Rayet, M., et al., 1091-1096, 1099, 1293-1294, 1367 annihilation of real electron-positron pairs into neutrino-antineutrino pairs, 1024-1033 calculation of the cross section for the process, 1024-1027, 1042-1050 heuristic approach, 1024-1027 in V-A theory, 1042-1050 due to the square of the lepton current in the Hamiltonian, 1025 reaction and energy-loss rates in a heuristic approximation, 1027-1029 reaction and energy-loss rates at non-relativistic electron energies, exact, 1028-1029 reaction and energy-loss rates at relativistic electron energies, exact, 1029-1031 reaction and energy-loss rates at highly relativistic electron energies, 1032-1033 reaction and energy-loss rates at modestly

relativistic electron energies, 1033

anticommutation relations, 1034, 1040 two component spinors, 1035 gamma matrices, 1040 Pauli spin matrices, 1034 Arnett, D., 1380, 1381, 1384 asymptotic giant branch (AGB) phase for low and intermediate mass models, 1166-1218, 1260-1290 for a 1 *M*<sub>☉</sub> model, 1166–1218 for a 5  $M_{\odot}$  model, 1260–1290 see AGB Austin, S., 1091 average hydrogen-burning luminosity during the TPAGB phase is between 6.9 and 10.3 times the average helium-burning luminosity, the exact ratio being a function of the rate of the triple alpha process relative to that of the C12(\alpha, \gamma)O16 process, 1205–1206 in a 1  $M_{\odot}$  model, Fig. 17.4.11, 1200 and Fig. 17.4.13, 1201 in a 5  $M_{\odot}$  model, Figs. 18.3.27 and 18.3.26, 1286 Bao, Z. Y., Beer, H., Käppeler, F., Voss, F., Wisshak, K., & Rauscher, T., 1295 basic physics of thermal conduction, 941-951 because of their small mass and consequent high velocities, electrons are dominant contributors to conductive heat transfer, 941 under electron-degenerate conditions, the number of participating electrons is proportional to  $(kT/\epsilon_F)$  but the electron ion cross section is proportional to  $(\epsilon/kT)^2$ , making heat transfer by conduction of major importance in electron-degenrate matter, 941 Be8: in the helium cores which develop in stars after the exhaustion of central hydrogen, the number abundance of Be8 in the ground state is related thermodynamically to the square of the number abundance of helium nuclei, 1081 Be8( $\alpha$ ,  $\gamma$ )C12<sup>\*\*</sup> reaction, where C12<sup>\*\*</sup> is the second excited state of C12, is a resonant reaction, 1081 - 1084Beaudet, G., Petrosian, V., & Salpeter, E. E., 1051, 1061, 1068

Becker, H. W., Kettner, K. U., Rolfs, C., & Trautvetter, H. P., 1363

1473		ndex
	<ul> <li>Becker, S. A., Iben, I., Jr., &amp; Tuggle, R. S., 1235, 1343</li> <li>beta decay and electron capture in stars at high densities, 979–1010</li> <li>introduction and formalism, 979–984</li> <li>capture at high densities, 984–989</li> <li>decay at high densities, 989–992</li> </ul>	C12** is C12 in the second excited state: its number abundance versus the number abundance of helium nuclei as given by assuming thermodynamic equilibrium is essentially the same as the steady state number abundance obtained by balancing creation and destruction rates, 1083
	positron decay and electron capture on a positron emitter, 993–1010	C12( $\alpha$ , $\gamma$ )O16 reaction- and energy-generation rates 1091–1092
	urca neutrino energy-loss rates, 1001-1007	C13 abundance peak and s-process nucleosynthesis
	experimental properties of beta-decay reactions	the peak in a 5 $M_{\odot}$ model, 1302–1313
	under terrestial conditions, 1009–1010	C13 abundance peak in TPAGB stars is formed by a mixing between freeh C12 and hydrogen after s
	Bethe, H. A., 1078	helium shell flash and subjecting the mix to
	Bjorken, J. D., & Drell, S. D., 1024, 1042 Bodansky, D., Clayton, D. D., & Fowler, W. A., 1384,	hydrogen burning, 1072, 1292, 1302–1313
	Bohr. N. 1072	formation of the peak and s-process
	Boltzmann transport equation, 894, 895–900, 915–918	nucleosynthesis in the peak in a 5 $M_{\odot}$ model, 1302–1313
	distribution function in, 895-896	C13( $\alpha$ , <i>n</i> )O16 reaction rate, 1094–1096
	moments of, 896, 897, 899, 907-909, 930-931	$C13(\alpha, n)$ O16 reaction releases neutrons in the helium-burning convective shell in TPAGB star
	Boltzmann transport equation, as used in calculating electron thermal conductivity, 956–972	when it is ingested by the shell at the start of a helium-shell flash, as demonstrated in a 5 $M_{\odot}$
	asymmetry in the electron distribution function, 957, 962	model, 1292–1293, 1329–1331 C13 number-abundance peak: is established in
	consequences of requiring zero electrical current, 962–968 cross section integral for electron-ion Coulomb	TPAGB stars in a region centered on the hydrogen-C12 interface formed during dredgeu following a helium shell flash, as exemplified in
	electrostatic field strength when the electrical	a 5 $M_{\odot}$ TPAGB model, 1302–1313 hydrogen and C12 mix across the initial
	the electrical field balances the gravitational field in such a way that it does not appear explicitly in	hydrogen-C12 interface and the product of the hydrogen and C12 number abundances peaks a the erstwhile interface 1302–1303
	the final equation for bulk acceleration, 968 Boltzmann, L., 940	hydrogen burning establishes a C13 abundance
	born again AGB star, 1395, 1460-1464	1303–1305
	Bowen, G. H., 1397	during the first part of the quiescent
	Bowers, D. L. & Salastar, E. E. 1421	hydrogen-burning phase, the C13 ( $\alpha$ , $n$ )O16
	Bowers, D. L., & Saipeter, E. E., 1451 Braaten, F. & Segel D. 1061 1062 1068	reaction releases neutrons in the C13 abundance
	branching ratios and the total cross section factor vs	1305–1313
	center of mass energy for O16+O16 nuclear reactions, Fig. 20.4.1, 1382	Cameron, A. G. W., 1078, 1091, 1094, 1291, 1292, 1384
	Breit-Wigner resonant cross section, 1072-1076	Canuto, V., 977
	bremstrahlung neutrino-antineutrino energy-loss process, 1051	Capella, Rigel, and Deneb define an observational band in the HR diagram corresponding to a
	bulk acceleration is determined by the difference between outward pressure gradient forces, inward gravitational forces, and inward and	theoretical band defined by models burning helium in a convective core, 1343–1342
	outward electrical forces, 900, 903	cross sections and reaction rates vs temperature f
	Burbidge, E. M., Burbidge, G. R., Fowler, W. A., & Hoyle, F., 1291, 1384	C12+C12 reactions, 1363–1366 reactions involving alpha particles released by the
	Burgers, J. W., 894	$C12 + C12 \rightarrow Ne20 + \alpha$ reaction and protons
	Buzzoni, A., Fusi-Pecci, F., Buononno, R., & Corsi, C. E., 1154	released by the C12 + C12 $\rightarrow$ Na23 + proton reaction, 1364–1366

1474 Index carbon burns quiescently in the core of a massive star 245.66 years after the peak of the first helium shell after helium is exhausted at the center, flash, Figs. 17.1.11-17.1.19, 1115-1123 1359-1371 25110 years after the peak of the first helium shell carbon in the Universe is produced by TPAGB flash, Figs. 17.1.20-17.1.22, 1124, 1126 (thermally pulsing AGB) stars, 1071, 72.214 years after the peak of the second helium 1222-1223, 1283-1285 shell flash after termination of evolution upward carbon-oxygen cores of intermediate mass AGB stars, along the red giant branch, Figs. 17.1.28-17.1.30, 1130-1131 1012 carbon production during helium shell flashes 20702 years after the peak of the second helium followed by dredgeup in TPAGB stars can shell flash, Figs. 17.1.31-17.1.33, 1132-1133 account for the existence of carbon stars and for 448 years after the peak of the sixth helium shell much of the carbon in the Universe, 1071, flash, Figs. 17.1.34-17.1.37, 1135-1137 1222-1223, 1281-1285 between the sixth minimum and seventh maximum Carr, W. J., 1429 in the helium-burning luminosity, 1.4875 million Caughlan, G. R., & Fowler, W. A., 1092, 1094, 1096, years after the peak of the first helium shell flash, 1099, 1293, 1294, 1363, 1379, 1383, 1384 Figs. 17.1.38-17.1.41, 1138-1139  $1.152 \times 10^5$  years after the peak of the seventh central star of a planetary nebula, 1397-1410 formed by superwind mass loss from a TPAGB star, helium shell flash, Figs. 17.1.42-17.1.47, 1395-1399 1142-1145  $1.290 \times 10^5$  years after the peak of the seventh evolves initially to the blue in the HR diagram at nearly constant luminosity. evolutionary track in helium shell flash, Fig. 17.1.48, 1146 the HR diagram of a theoretical example is nearly on the zero age horizontal branch, Figs. 17.1.49-17.1.51, 1147-1148 shown in Fig. 21.3.1, 1398 emits many photons with energies greater than the characteristics vs mass of a 1  $M_{\odot}$  model burning ionization potential of hydrogen; collisions hydrogen in a shell and helium in a convective between free electrons and ions produces core during the horizontal branch phase, low-lying atomic levels, and subsequent radiative Figs. 17.2.1-17.2.21, 1149-1165 transitions between low-lying atomic levels on the ZAHB, Figs. 17.2.1-17.2.3, 1149-1150 produce visible light, 1399 nearly halfway through the HB phase, lifetime of the circumstellar envelope as a visible Figs. 17.2.9-17.2.11, 1157-1158 planetary nebula, 1399-1403 slightly over halfway through the HB phase, see PNN Figs. 17.2.12-17.2.14, 1159-1160 central temperature vs central density for models of experiencing a final spurt of convective core growth mass 1, 5, and 25  $M_{\odot}$  during nuclear burning near the end of the HB phase, phases, Fig. 20.1.4, 1345 Figs. 17.2.15-17.2.17, 1161-1162 Cepheid instability strip in the HR diagram, near the end of the core helium-burning phase, 1234-1235, 1342-1343, Fig. 20.1.2, 1341 Figs. 17.2.19-17.2.21, 1164-1165 intersection with the core helium-burning band characteristics vs mass of a  $1M_{\odot}$  model near defines where most Cepheids of a given minimum hydrogen-burning luminosity during composition will be found, 1234-1235 the EAGB phase, Figs. 17.2.24-17.2.28, Cepheid variables, 1342-1343 1168-1170 period-mass-radius relationships, 1342 characteristics vs mass of a  $1M_{\odot}$  model on the period-luminosity-mass-surfacetemperature thermally pulsing asymptotic giant branch relationships, 1342 (TPAGB), 1171-1218 Chapman, S., & Cowling, T. G., 894, 937 beginning the first helium shell flash, Figs. 17.2.29-17.2.33, 1171-1174 characteristics vs mass of a 1  $M_{\odot}$  model during the core helium flash phase after ignition of helium before, during, and after the first helium shell flash off center in a hydrogen-exhausted, on the AGB, Figs. 17.3.4-17.3.11, electron-degenerate core, Figs. 17.1.1-17.1.51, 1177-1187 1104-1148 luminosity profiles vs mass at several times during near the tip of the red giant branch, and between the first two of the fifth set of thermal pulses, Fig. 17.4.5, 1194 Figs. 17.1.1-17.1.3, 1104-1106 12.694 hours after the peak of the (first) helium structure variables and abundances vs mass when shell flash which terminates evolution upward surface luminosity near its minimum after the along the red giant branch, Figs. 17.1.5-17.1.12, ninth set of thermal pulses. 1109-1115 Figs. 17.4.16-17.4.17, 1203-1204

Index 1475 structure variables and abundances vs mass when structure and composition in and near the the hydrogen-burning luminosity is near its hydrogen-burning shell, Fig. 21.6.7, 1438 maximum before the tenth set of thermal pulses, structure and composition variables below the Figs. 17.4.18-17.4.19, 1204, 1205 H-burning shell, Fig. 21.6.8, 1439 abundance profiles vs mass compared for models at neutrino-antineutrino energy-loss rates due to different times centered on the ninth and tenth various weak interaction processes, electron sets of thermal pulses, Figs. 17.5.1-17.5.3, Fermi energy over kT, and radiative and 1207-1208 conductive opacities below the base of the hydrogen-burning shell, Fig. 21.6.9, 1439 energy-generation rates and composition vs mass at gravothermal energy-generation rate and its five times during the eleventh set of thermal pulses, Figs. 17.5.4-17.5.8, 1211-1213 ingredients, helium-burning energy-generation abundances of carbon isotopes vs mass below the rate, neutrino-antineutrino energy-loss rate, and luminosity below the H-burning shell, H-burning shell at the end of the tenth interpulse Fig. 21.6.10, 1440 phase, Fig. 17.6.1, 1215 characteristics vs mass of a white dwarf model of abundances vs  $M_{CS}$ , the mass of the convective mass 0.565  $M_{\odot}$  approximately (1)  $1.1 \times 10^7$  yr, shell, of isotopes relevant to neutron production (2)  $1.8 \times 10^8$  yr, (3)  $1.5 \times 10^9$  yr, and and s-process nucleosynthesis in the convective (4)  $7.5 \times 10^9$  yr after having been the central star shell during the first of the eleventh set of helium of an observable planetary nebula, shell flashes, Table 17.6.1, 1216 Figs. 21.6.11-21.6.22, 1444-1453 structure vs mass in the convective shell of a 1  $M_{\odot}$ structure and composition in and near the AGB model just after peak helium-burning hydrogen-burning shell, (1) Fig. 21.6.11, 1444; luminosity during the eleventh set of thermal (2) Fig. 21.6.15, 1448; (3) Fig. 21.6.19, 1450; pulses, Fig. 17.6.2, 1217 and (4) Fig. 21.6.21, 1453 characteristics vs mass of a model PNN of mass structure and composition variables below the  $0.565 M_{\odot}$  derived by mass loss from a 1  $M_{\odot}$ hydrogen-burning shell, (1) Fig. 21.6.12, 1444; TPAGB model: (1) at the beginning and (2) at the (2) Fig. 21.6.16, 1448; (3) Fig. 21.6.20, 1451; end of the observable stage of the nebula, and (4) Fig. 21.6.22, 1453 Figs. 21.3.5-21.3.12, 1404-1410 neutrino-antineutrino energy-loss rates due to structure and composition in the interior, various weak interaction processes, electron Fig. 21.3.5, 1404, & Fig. 21.3.6, 1405 Fermi energy over kT, and radiative and energy-generation rates below the base of the conductive opacities below the base of the hydrogen-burning shell, Figs. 20.3.7-20.3.8, hydrogen-burning shell, (1) Fig. 21.6.13, 1445; 1406 (2) Fig. 21.6.17, 1449 structure and composition in outer layers, gravothermal energy-generation rate and its Figs. 21.3.9 & 21.3.10, 1407, 1408 ingredients, helium-burning energygeneration structure and composition in and near the rate, neutrino-antineutrino energy-loss rate, and hydrogen-burning shell, Figs. 21.3.11-21.3.12, luminosity below the hydrogen-burning shell, 1408-1409 (1) Fig. 21.6.14, 1445; (2) Fig. 21.6.18, 1449 characteristics vs mass of a model PNN of mass characteristics at the center of the hydrogen-burning  $0.565 M_{\odot}$  approximately 10<sup>5</sup> yr after the shell during PNN and white dwarf evolution beginning of the observable stage of the nebula (mass and radial location, state variables, and and approximately  $9 \times 10^4$  yr after the end of the hydrogen-burning luminosity), Table 21.6.1, observable stage, Figs. 21.6.2-21.6.5, 1434-1436 1437 structure and composition below the characteristics vs mass of a 5  $M_{\odot}$  model during the hydrogen-burning shell, Figs. 21.6.2-21.6.3, combined core helium-burning and shell 1434-1435 hydrogen-burning phase, 1223-1232 energy-generation rates below the base of the structure variables, abundances, and gravothermal hydrogen-burning shell, Fig. 21.6.4, 1435 energy-generation rates halfway through the core structure and composition in and near the helium-burning phase, Figs. 18.1.2-18.1.6, hydrogen-burning shell, Fig. 21.6.5, 1436 1224-1227 characteristics vs mass of a white dwarf model of temperature-pressure gradients and ingredients of mass 0.565  $M_{\odot}$  approximately 2 × 10<sup>6</sup> yr after the radiative gradient vs mass, 50%, 67%, 75%, having been the central star of an observable and 84% of the way through the core planetary nebula, Figs. 21.6.7-21.6.10, helium-burning phase, Fig. 18.1.6, 1227, 1438-1440 Figs. 18.1.9-18.1.11, 1229-1230

Index 1476 characteristics vs mass of a 5  $M_{\odot}$  model during the gravothermal energy-generation rates and rates of combined core helium-burning and shell change of state variables vs mass at the hydrogen-burning phase (cont.) beginning and near the end of dredgeup after the number abundances of major constituents vs mass thirteenth helium shell flash, Figs. 18.3.20-18.23.1280-1282 84% of the way through the core helium-burning carbon-abundance profiles before and after the phase, Fig. 18.1.12, 1232 characteristics vs mass of a 5  $M_{\odot}$  model during the fifteenth helium shell flash, Fig. 18.3.25, 1285 transition from the core helium-burning phase to characteristics vs mass in a 25  $M_{\odot}$  model during the the EAGB phase, 1235-1241 core helium-burning phase: (1) at the beginning, (2) halfway through, (3) near the end while the luminosity vs mass at three times: before, during, and after the transition, Fig. 18.2.2, 1237 mass of the convective core is still increasing, and (4) near the end as the mass of the convective structure and composition variables and core begins to decrease, 835, Vol. 1, 1346-1355 gravothermal and nuclear energy-generation rates vs mass, Figs. 18.2.3-18.2.5, 1238-1239 structure variables and hydrogen and helium abundances: (1) Fig. 11.3.17, 835, Vol. 1; characteristics vs mass of a 5  $M_{\odot}$  model during the (2) Fig. 20.2.1, 1347; (3) Fig. 20.2.3, 1348; early asymptotic giant branch (EAGB) phase, (4) Fig. 20.2.5, 1349 1239-1260 temperature-pressure gradients and the radiative gravothermal and nuclear energy-generation rates T-P gradient and its ingredients (1) Fig. 11.3.18, vs mass near the start of the phase while burning 835, Vol. 1; (2) Fig. 20.2.2, 1347; (3) Fig. 20.2.4, helium and hydrogen in shells, Fig. 18.2.6, 1239 gravothermal and nuclear energy-generation rates 1348; and (4) Fig. 20.2.6, 1349 gravothermal energy-generation rates vs mass vs mass as hydrogen burning dies out, halfway through the core helium-burning phase, Fig. 18.2.7, 1240 Figs. 20.2.7-20.2.7a, 1351 structure and composition variables and number abundances of major constituents near the gravothermal and nuclear energy-generation rates vs mass near the minimum in the end of the core helium-burning phase as the mass of the convective core has begun to decrease, hydrogen-burning luminosity, Figs. 18.2.13-18.2.16, 1247-1250 Fig. 20.2.8, 1353 s-process element production due to activation of characteristics vs mass of a 5  $M_{\odot}$  model during the the  ${}^{22}Ne(\alpha, n){}^{25}M_g$  neutron soarce, transition from the EAGB phase to the TPAGB 1353-1359 phase: structure and composition; characteristics vs mass in a 25  $M_{\odot}$  model in which thermodynamic characteristics; nuclear, gravothermal, and neutrino energy-generation helium has vanished over a large region which rates, Figs. 18.2.19-18.2.27, 1253-1260 was earlier contained in a convective core and is characteristics vs mass of a 5  $M_{\odot}$  model during the now contracting gravitationally to provide most of the energy emanating from the surface. helium thermally pulsing asymptotic giant branch (TPAGB) phase, 1260-1290 burning has been temporarily almost extinguished and the model begins evolving temperature-pressure gradients, ingredients of the upward in the HR diagram along a red supergiant radiative gradient, and hydrogen and helium branch, 1355-1358 abundances vs mass at three times: after the tenth helium shell flash, with and without convective structure variables, nuclear and gravothermal overshoot, just prior to the peak of the eleventh energy-generation rates, and isotopic number flash, and during dredgeup after the eleventh abundances, Figs. 20.2.9-20.2.11, 1357-1358 shell flash, convective overshoot invoked, hydrogen-burning, helium-burning, gravothermal, Fig. 18.3.7, 1266, Fig. 18.3.9, 1270, and and neutrino-antineutrino luminosities are, respectively, 17.8%, 0.4%, 82.8%, and -1% of Fig. 18.3.11, 1271 number abundances vs mass 11 years after the surface luminosity, Fig. 20.2.9, 1357 maximum L<sub>He</sub> during the eleventh helium shell in the erstwhile convective core, for every seed flash, Fig. 18.3.10, 1270 nucleus, 1.5 neutrons have been captured to form luminosity profiles vs mass at several times during heavy s-process elements. neutrons are the the eleventh helium shell flash, consequence of  $(\alpha, n)$  reactions on Ne22, Fig. 20.2.11, 1358 Figs. 18.3.12-18.3.13, 1271-1272 opacity, P/Prad, luminosity, Vrad, radius, and characteristics vs mass in a 25  $M_{\odot}$  model with a temperature vs mass at eight times during helium-exhausted core in which densities and temperatures are such that electron-positron pairs dredgeup after the thirteenth helium shell flash, Figs. 18.3.14-18.3.19, 1274-1277, 1279 are abundant and produce neutrino-antineutrino

1477		ndex
1477	<ul> <li>pairs which carry off energy at a huge rate. gravothermal energy release in the core supplies the energy lost to neutrinos with enough to spare to make a substantial contribution to the surface luminosity. helium burning has been resurrected in a shell, sustaining convection in an overlying shell and making a substantial contribution to the surface luminosity. carbon burning has begun in the core. The model expands as a red supergiant and envelope convection extends inward almost to the convective shell for which helium burning in a shell is responsible. absorption of energy from the flux of energy between the helium-burning shell and the base of the convective envelope provides the energy necessary for envelope expansion, Figs. 20.3.1–20.3.3, 1359–1362</li> <li>structure variables, hydrogen and helium abundances, nuclear and gravothermal energy-generation rates, and rates of neutrino energy loss by weak interaction processes vs mass, Figs. 20.3.1–20.3.4, 1359–1362</li> <li>hydrogen-burning has been effectively extinguished, carbon-burning, helium-burning, gravothermal, and neutrino luminosities are, respectively, 20.2%, 124.9%, 216.8%, and –262% of the surface luminosity, Figs. 20.3.1–20.3.2, 1359–1361</li> <li>in the core, energy losses due to escaping neutrino-antineutrino pairs produced by electron-positron annihilation and by the photoneutrino process are nearly exactly balanced by the release of gravothermal energy, Fig. 20.3.3, 1361–1362</li> <li>reactions between two C12 nuclei produce Ne20 and Na23 with the emission, respectively, of an alpha particle and a proton. approximately one third of the nuclear energy liberated during carbon burning comes from the initiating reactions and two thirds comes from reactions involving captures of the emitted alpha particles and protons, 1364, Fig. 20.3.4, 1364</li> </ul>	ndex structure variables and hydrogen and helium number abundances vs mass, Fig. 20.3.6, 1368 gravothermal energy-generation rate and its ingredients, nuclear energy-generation and neutrino energy loss rates, Figs. 20.3.7–20.3.8, 1369–1370 weak interaction neutrino-antineutrino loss rates and dominated by the electron-positron pair annihilation process, Fig. 20.3.9, 1370–1371 inside the convective core, neutrino losses are supplied primarily by the release of energy by carbon-burning reactions, outside of the core neutrino losses are supplied primarily by gravothermal energy release, Fig. 20.3.8, 1369–1371 characteristics vs mass in a 25 $M_{\odot}$ model burning carbon and helium in shells in a core in which contraction and heating is driven by energy loss by neutrino-antineutrino pairs, Figs. 20.3.10–20.3.17, 1371–1380 structure variables and O16, C12, He4, and H1 abundances. global luminosities (in solar units) are $L_{\nu\nu} = -2.23/7, L_{CB} = 2.03/7,$ $L_{grav} = 1.52/6, L_{He} = 6.98/5, and$ $L_s = 2.43/5,$ Figs. 20.3.10–20.3.11, 1372 the gravothermal energy-generation rate and its ingredients vs mass in the contracting core which contains a carbon-burning shell and a helium-burning shell. energy fluxes due to nuclear burning support convective regions above the nuclear burning regions, Figs. 20.3.12–20.3.13, 1373 nuclear and gravothermal energy-generation rates and the neutrino-antineutrino energy-loss rate in and near the carbon-burning shell, Figs. 20.3.14–20.3.15, 1374 weak interaction neutrino antineutrino loss rates are dominated by the electron-positron pair annihilation process in and above the carbon-burning shell, Fig. 20.3.10, 1375 number abundances of various isotopes vs mass over the inner 8 $M_{\odot}$ , Fig. 20.3.17, 1375 number abundances of various isotopes vs mass over the inner 2 $M_{\odot}$ , Table 20.3.3, 1376 the primary nucleosynthesis result of complete
	1365 near the center, N13 experiences photodisintegration into C12 and a proton and proton capture reactions (mostly CNO cycle reactions) produce energy at rates comparable to C12+C12 reactions, 1365–1367, Fig. 20.3.4.	the primary nucleosynthesis result of complete carbon burning is to convert a mixture of C12 and O16 into a mixture of O16 and Ne20, 1378–1380 charged current weak interaction Hamiltonian, 1013–1019, 1020–1024
	<ul> <li>1365</li> <li>temperature-pressure gradient and its ingredients vs mass, Fig. 20.3.5, 1368</li> <li>characteristics vs mass in a 25 M<sub>☉</sub> model burning carbon in a small convective core and helium in a shall Fig. 20.3.6, 20.3.9, 1367, 1371</li> </ul>	argument for one coupling constant in muon decay, 1020–1024 argument for two coupling constants in nuclear beta decay, 1013–1019 simple form of Hamiltonian and of transition probability in nuclear beta decay, 1013–1017

1478		ndex
	-	
	charged current weak interaction Hamiltonian ( <i>cont.</i> ) the products of lepton currents (square products) produce reactions which have not been observed in the laboratory but which play important roles in stars, 1012, 1025	an increase in average mass occurs during the cor helium-burning phase because the number abundance per gram of free electrons in the convective core remains constant and it is the increase with time in the average
	the products of nucleon and lepton currents (cross products) produce nuclear beta-decay reactions which occur in the laboratory, 1013–1014	primarily responsible for the increase in core mass
	Chiu, H. Y., 1050, 1052	the convective core mass $M_{\rm CC}$ of a core
	Chiu, H. Y., & Morrison, P., 1050 Chiu, H. Y., & Stabler, R. C., 1026, 1051	helium-burning model can decrease semi-periodically although the average mass
	circumstellar envelope formed about a TPAGB star by	decreases in $M_{CC}$ may be accompanied by the
	a superwind, 1395–1399 observability and lifetime as a planetary nebula, 1399–1403	appearance of a convective shell; this behavior due to the parabolic shape of the radiative
	superwind is due to shocks generated by acoustical	gradient $V_{\rm rad}$ , 1228–1231
	pulsations and radiation pressure on grains, 1397 clump branch is the metal-rich equivalent of the	convective overshoot occurs at the base of the convective envelope of a TPAGB star when the base reaches the H-He interface, 1222–1223,
	metal-poor horizontal branch, lying close to the	1265–1280
	red giant branch during the entire core	Cook, C. W., Fowler, W. A., Lauritsen, C. C., & Lauritsen T 1078
	helium-burning phase, 1152–1153	core helium shell flashes in a 1 $M_{\odot}$ model during
	$101 \text{ a } 1 \text{ M}_{\odot}$ Inodel, 1149–1155	evolution from the red giant branch to the
	amplitude of wave function vs time, 1073	horizontal branch, 1104-1149
	1074–1075	Coulomb barrier inhibition of nuclear reactions
	crossing time, 1073, 1077, 1079, 1080, 1085	between charged particles, 1070
	equilibrium configuration, 1073 partial energy widths and decay lifetimes, 1073	coulomb binding energy between ions and degeneral electrons divided by kT vs mass in a white dwa model of mass $0.565M_{\odot}$ after $1.5 \times 10^9$ vr and
	for a non-relativistic electron gas, Table 13.6.1,	$7.5 \times 10^9$ yr of evolution, Fig. 21.6.23, 1455 Coulomb distorted plane waves for electrons and
	974	positrons, 981, 993
	nts to sophisticated estimates, 9/5–9/8	Coulomb forces between electrons and ions and the
	definition of 942	Wigner-Seitz sphere in electron-degenerate
	elementary estimates of, 943–951	matter, 1411–1412
	quantitative estimates, 975-978	matter 994
	analytic fits to sophisticated estimates, 975–978	crossing time in a compound nucleus versus the compound nucleus lifetime, 1077, 1079, 1080
	electrons not degenerate, 970–971 electrons degenerate, but not relativistic, 971–972	cross section factor for resonant nuclear reactions, 1077–1078
	electrons not relativistic, arbitrary degeneracy, Table 13.6.1, 974	electron-positron pair into a neutrino-antineutrino pair, 1026, 1049
	electrons relativistic, 977–978	derivation, 1024-1026, 1042-1050
	convective core in intermediate-mass and massive	heuristic, 1024–1026
	stars grows or snrinks according to the nature of the change in number abundances in	in V-A theory, 1042–1050
	consequence of nuclear burning, 1220–1221	cross section for scattering by Coulomb forces, 916, 943–947
	a decrease in mass occurs during the core hydrogen-burning phase because the number abundance per gram of free electrons in the convective core decreases with time causing the	cross sections for resonant nuclear reactions, 1075–1076, 1078, 1080, 1082
	electron-scattering contribution to opacity to	D'Antona, F., & Mazzitelli, I., 1466
	decrease more rapidly than the average	Debye length, 917
	energy-generation rate in the core increases	Debye, P., 1412

	index
Debye theory, terrestial metals, and stell 1412–1426 normal modes, phonons, and equation 1413–1415 Debye temperature $\Theta_{Debye}$ is related sound speed and to a maximum fre inversely proportional to the separa adjacent ions, 1414–1415 specific heat at low temperatures is pr the cube of the temperature divided 1414	tr interiors, s of state, b opportional to by $\Theta_{\text{Debye}}$ , diffusion, observational evidence for, 893 Li7 at the Sun's surface is many times smaller that in the Solar system, 647, Vol. 1, 893 Fe at the Sun's surface is smaller than the interior abundance inferred by comparing predicted Sol neutrino fluxes with detected fluxes, 682, Vol. 1 893 white dwarf surface abundances are often monoelemental, 893, 1456 diffusion out of the Solar convective envelope, 925–933
Debye temperature for terrestial solid Table 21.4.1, 1415 Debye temperature in the stellar contr 1415–1418 vibration amplitude, ion separation, a point in terrestial solids, 1417, 142 Table 21.4.2, 1417 application of the Thomas-Fermi mod atom, 1420–1426 diffusion and the formation of a monoel surface abundance in white dwarfs DA, DB, and DQ white dwarfs have, essentially pure hydrogen, helium, spectra, 1456 the gravitational acceleration at the su typically over 1000 times larger the and the time scale for gravitational the order of $10^7$ yr as opposed to o $10^{10}$ yr in surface layers of the Sur diffusion time scales at $7 \times 10^{-4} M_{\odot}$ surface of an $0.565 M_{\odot}$ model whit times 1.05, 20.7, 112, and 1820 tim after the initiation of the planetary are between 2.3 and 3.4 times $10^7$ 21.7.1, 1457	y 223–933 timescales for, 926, 929–930 velocities at the base of the convective envelope, y 925–933, Table 12.10.1, 932 diffusion velocities, 906–909, 918–929 effect of including electron flow properties, 918–922 effect of ion-electron interactions, 918–922 effect of ion-electron interactions, 918–922 effect of ion-electrons and positrons, 1033–103 mental solutions, 1034–1039 Dirac, P. A. M., 1034 espectively, and carbon in the Sun settling is of the order of 1394 below the e dwarf at es 10 <sup>5</sup> yr ebula stage r, Table warf with
abundance profiles in a model while of diffusion taken explicitly into acco that, after $2.76 \times 10^5$ yr of evolution profiles have not been affected not diffusion, but after $4.56 \times 10^8$ yr of the surface has become pure hydro abundances have been dramatically the outer 10% of the mass of the m below the base of the initial helium	warr with nt shows n, abundance weally byenvelope is ejected, 1350dredgeup (second) during the EAGB phase in a 5 $M_{\rm e}$ model star, 1221, 1250–1252 degrees of dredgeup during the first and second dredgeup episodes are compared in Table 18.2. 1252en and altered over del, to well1252 dredgeup (third) during the TPAGB phase in a 1 $M_{\odot}$ model star, 1206–1214
Fig. 21.7.1, 1458 diffusion, causes of, 893, 901–902 abundance gradients, 901–902 gravitational forces, 901–902 temperature gradients, 901–902	model star, 1260–1290 convective overshoot occurs when the base of the convective envelope reaches the hydrogen-helium interface, 1222–1223,
diffusion coefficients, 901–902 diffusion, driving forces for, 911–914 diffusion equations, algorithms for solv equations for abundance changes, 93 algorithms for solving equations, 937	1205–1280changes in surface abundances due to dredgeup, 1281–1284ag, 933–940-936enhancements vs strength of the helium shell flash, Table 18.3.1, 1284

1480		ndex
	Dubbers, D., Mampe, W., & Döhner, J., 1019 Dulong, P. L., & Petit, A. T., 1451 during the TPAGB phase, the average hydrogen-burning luminosity is 7–10 times the average helium-burning luminosity, 1205–1206 in a 1 $M_{\odot}$ model, Fig. 17.4.11, 1200, & Fig. 17.4.13, 1201 in a 5 $M_{\odot}$ model, Figs. 18.3.26 and 18.3.27, 1286	electrostatic binding energy between electrons and heavy ions in electron-degenerate matter, 1410–1412 binding energy per ion divided by kT is traditionally designated by $\Gamma$ , 1411 transition between liquid and solid in pure oxygen occurs for $\Gamma$ in the range 150–250, Table 21.4.3 1411 transition between gas and liquid occurs for $\Gamma \simeq \Gamma_{mat}/9$ 1452
	<ul> <li>EAGB (early AGB) phase follows when helium is exhausted at the center. Helium burns in a shell, hydrogen-burning is extinguished, and the base of the convective envelope extends inward to regions where products of complete hydrogen burning exist, leading to a second dredge-up episode, 1153, 1167–1171, 1235–1260</li> <li>details for a 1 <i>M</i><sub>☉</sub> model, Fig. 17.2.5, 1153, 1167–1171</li> <li>details for a 5 <i>M</i><sub>☉</sub> model, 1235–1260</li> <li>helium shell mass-luminosity relationship, eq. (18.2.7), 1245</li> <li>CO core mass-radius relationship, eq. (18.2.9), 1246</li> <li>electric charge neutrality in an ionized medium is maintained by a macroscopic electric field, 941, 951–956</li> <li>however, the divergence of the field is not zero, revealing an excess positive charge corresponding to approximately one extra positive charge for every 2 × 10<sup>36</sup> protons, 953</li> <li>electron capture on a positron emitter, 995–1000</li> </ul>	$\Gamma \sim \Gamma_{melt}/9, 1432$ Γ at the center of a model CO white dwarf as a function of age, Table 21.6.2, 1447 transition between gaseous and liquid state in a model CO white dwarf of mass 0.565 <i>M</i> <sub>☉</sub> occur at between ~ 10 <sup>7</sup> yr and ~ 10 <sup>8</sup> yr of evolution, 1452 transition between liquid and solid state in a mode CO white dwarf of mass 0.565 <i>M</i> <sub>☉</sub> begins at the center after ~ 2 × 10 <sup>9</sup> yr of evolution, 1455 Γ vs mass in an 0.565 <i>M</i> <sub>☉</sub> model white dwarf after 1.5 × 10 <sup>9</sup> and 7.5 × 10 <sup>9</sup> yr of evolution, Fig. 21.6.23, 1455 electrostatic field in ionized matter in a gravitational field, 951–956 a single, completely ionized, species, perfect gas equation of state, 952–953 mixture of ionized species, electrons degenerate, 955–956 unique determination of field strength requires specification that electric current vanishes, 951
	<ul> <li>electrons degenerate, 999–1000</li> <li>electrons not degenerate, 995–999</li> <li>example of N13 + e<sup>-</sup> → C13 + antineutrino, Table 14.6.1, 1000</li> <li>electron contribution to the rate of gravitational energy generation in white dwarfs, 1442–1443, 1446</li> <li>contribution of electrons relative to contribution of ions is proportional to (kT/ϵ<sub>Fermi</sub>) times (Y<sub>e</sub>/Y<sub>ions</sub>), where Y<sub>e</sub> and Y<sub>ions</sub> are, respectively, the number abundances of electrons and ions, 1443</li> <li>electron decay and capture on a positron-stable nucleus at high densities, 975–995</li> <li>electron decay, 989–995</li> <li>typical examples, C14 → N14 + e<sup>-</sup> + antineutrino, N14 + e<sup>-</sup> → C14 + neutrino, 975</li> <li>electron-positron annihilation in electron-degenerate matter releases twice the rest mass energy of an electron plus the electron Fermi energy, regardless of which electron is destroyed, 994</li> <li>electron-positron pair formation, 1012</li> </ul>	electrostatic field strength determination for a completely ionized monatomic gas assuming a perfect gas equation of state separately for ions and electrons, 952 assuming that the gradient of the electron pressure balances the total gravitational and electrical forces on electrons and that the same holds true for positive ions, one can solve for the electrical field strength, 952 the divergence of the electrostatic field is finite, revealing a net electrical charge density, 953 the excess charge corresponds to approximately or extra positive charge for every $2 \times 10^{36}$ protons a ratio which approximates the ratio of the gravitational force between two protons and the strength of the electron and ion pressure gradients equals the total gravitational force on the electrons and ions, independent of the electrical field strength under electron-degenerate conditions, 955–956

1101		
	-	
	the electrical force on an electron equals the gravitational force on an ion and the net external force on an ions vanishes!!!, 956	evolutionary track in the HR diagram of a 5 $M_{\odot}$ model during the core helium-burning phase, second approximation, Fig. 18.1.16, 1234 track during the EAGB and TPAGB phases
	equilibrium prevail, 909–911	Fig. 20.1.2, 1341
	<ul> <li>Endt, P. M., &amp; van der Leun, C., 1010</li> <li>energy levels in nuclei involved in the triple alpha process and in the C12(α, γ)O16 reaction,</li> <li>Fig. 16.2.1, 1079</li> <li>energy widths and lifetimes of nuclear states, 1073</li> </ul>	evolutionary track in the HR diagram of a 25 $M_{\odot}$ model through core hydrogen burning, core helium- and shell hydrogen-burning, and core and shell carbon-burning stages, Fig. 20.1.1, 1340
	equation of state for phonons in electron-degenerate matter, 1429, 1429–1433	evolutionary tracks in the HR diagram of 1, 5, and $25 M_{\odot}$ models during hydrogen and helium muchaer huming phases. Fig. 20.1.2, 1341
	equilibrium ratio of two isotopes is a function of temperature, 1385–1388	evolution of a 1 $M_{\odot}$ model burning helium and
	the abundance of the neutron-rich member of an isobar increases relative to the abundance of the proton-rich member with increasing temperature, 1388	outline of evolution from the onset of core helium burning to the TPAGB phase, 1103–1104 evolution of a 1 $M_{\odot}$ model from the the onset of core
	the neutron to proton ratio in the isotope mix prevailing after a nuclear burning phase increases	helium burning to the start of the horizontal branch phase, 1104–1149
	with each successive nuclear burning phase, 1388 Erozolimskii, B. G., & Mostovoi, Yu. A., 1019 evolutionary behavior as a function of stellar mass: low ( $<2.25 M_{\odot}$ ), intermediate ( $2.25 M_{\odot}$ to 10.5 $M_{\odot}$ ), and large ( $>10.5 M_{\odot}$ ), 1101–1218, 1391–1471, 1220–1290, 1291–1338,	time variation of the helium-burning luminosity and of the surface radius and luminosity before, during, and after the first helium shell flash which terminates evolution upward in the HR diagram along the red giant branch, Fig. 17.1.4, 1107
	1339–1390 low mass: develop an electron-degenerate helium core after exhaustion of hydrogen at the center, become TPAGP stars with an electron-degenerate CO core, experience a superwind containing nitrogen and <sup>3</sup> He, and become CO white dwarfs of mass co 0.55 – 0.65	velocity and acceleration, and gravitational acceleration vs time near the temporal and spatia peak and into the decay phase of the first core helium shell flash, Figs. 17.1.9–17.1.12, 1113–1116 time variation of global and interior characteristics during the series of seven core belium flashes
	$M_{\odot}$ , 1101–1218, 1391–1471 intermediate mass: burn helium in a non electron-degenerate core, become TPAGB stars	experienced by the model evolving from the tip of the red giant branch to the horizontal branch, Figs. 17.1.23–17.1.27, 1126–1129
	with an electron-degenerate CO or ONe core, experience a superwind containing freshly made	evolution of a 1 $M_{\odot}$ model during the horizontal branch (HB) phase, 1149–1167
	carbon and s-process elements, and become CO white dwarfs of mass $\sim 0.65 - 1.37 M_{\odot}$ , 1220–1290, 1291–1338	time evolution of various interior and global characteristics during the HB phase, Fig. 17.2.4, 1151, Figs. 17.2.6–17.2.8, 1154–1157, Fig. 17.2.18, 1162
	core, then carbon in a non electron-degenerate core, experience core collapse and evolution into a neutron star or black hole after ejecting a heavy	evolution of a 1 $M_{\odot}$ model during the early asymptotic giant branch (EAGB) phase, 1166–1171
	explosion, 1339–1390 evolutionary track in the HR diagram of a 1 Mo	characteristics from the end of the HB phase
	model during red giant branch, horizontal branch (HB, clump), and asymptotic giant branch phases, Fig. 17.2.5, 1153	1166–1167 evolution of a 1 $M_{\odot}$ model before, during, and after the first helium shell flash during the first therma
	evolutionary track in the HR diagram of a 5 $M_{\odot}$ model just prior to and during the core helium-burning and shell hydrogen-burning phase as a red giant, first approximation,	pulse on the asymptotic giant branch (AGB), 1175–1190, Figs. 17.3.1–17.3.12, 1175–1190 time evolution of global luminosities, radius, and surface temperature, Figs. 17.3.1–17.3.3,

1482	Index		
	-		
	evolution of a 1 $M_{\odot}$ model before, during, and after the first helium shell flash during the first thermal pulse on the asymptotic giant branch (AGB)	mass of the convective core vs time during the core helium-burning phase, second approximation, Fig. 18.1.8, 1229	
	( <i>cont.</i> ) luminosity profiles vs mass at several times, Fig. 17.3.4, 1177, Figs. 17.3.8–17.3.9,	temperature-pressure gradients and ingredients of the radiative gradient vs mass at three times: 67%, 75%, and 84% of the way through the core	
	1183–1184 global luminosities at several times, Table 17.3.1, 1188	helium-burning phase, Figs. 18.1.9–18.1.11, 1229–1230 state variables at the model center vs time,	
	nuclear and gravothermal energy-generation rate profiles vs mass at several times,	Fig. 18.1.13, 1232 number abundances at the model center vs time,	
	Figs. 17.3.10–17.3.11, 1185–1187 variation with time of the rate at which nuclear	Fig. 18.1.14, 1233 global luminosities and the helium abundance at th	
	energy stored as gravothermal energy during the helium-burning flash flows into the base of the convective envelope, Fig. 17.3.12, 1189–1190	model center vs time, Fig. 18.1.15, 1233 evolution of a 5 $M_{\odot}$ model transitioning from the core helium-burning to the EAGB phase, 1235-1242	
	pulsing asymptotic giant branch (TPAGB) phase, systematics, 1191–1206	global luminosites vs time, Fig. 18.2.1, 1236 luminosity vs mass at three times, Fig. 18.2.2,	
	global luminosities vs time during the first five sets of thermal pulses, Figs. 17.4.1–17.4.6, 1191–1194	1237 evolution of a 5 $M_{\odot}$ model during the early asymptotic giant branch (EAGB) phase,	
	luminosity profiles vs mass at several times during and between the first two of the fifth set of pulses, Fig. 17.4.5, 1194	state variables at the center of and mass of the helium-burning shell vs time, Fig. 18.2.8,	
	global luminosities at several times during and between the first two of the fifth set of pulses, Table 17.4.1, 1195	1242 helium abundance at the center of and at mass boundaries of the helium-burning shell vs time, Fig. 18.2.9, 1243	
	the sixth-ninth sets of thermal pulses, Figs. 17.4.7–17.4.10, 1198–1199	surface luminosity and radius vs time, Fig. 18.2.10 1244	
	global luminosities vs time over the course of 10 sets of thermal pulses, Figs. 17.4.11–17.4.15, 1200–1202	helium-burning luminosity and model radius vs mass of the helium-burning shell, Fig. 18.2.11, 1245	
	surface luminosity and mass at the center of the hydrogen profile vs time over the course of 10	global luminosities vs time, Fig. 18.2.12, 1246	
	sets of thermal pulses, Fig. 17.4.15, 1202 abundance profiles vs mass compared for models at different times centered on the ninth and tenth sets of thermal pulses, Figs. 17.5.1–17.5.3, 1206–1209	time variation of the mass at the base of the convective envelope, the mass at the center of th hydrogen profile, and the mass at the center of the helium-burning shell, Fig. 18.2.17, 1250	
	evolution of a 5 $M_{\odot}$ model from the the onset of the core helium-burning (and shell hydrogen-burning) phase into the thermally	<ul> <li>time variation of state variable at the center and the neutrino luminosity, Fig. 18.2.18, 1253</li> <li>evolution of a 5 M<sub>☉</sub> model transitioning from the</li> </ul>	
	pulsing asymptotic giant branch (TPAGB) phase, 1220–1290 evolutionary track in the HB diagram just prior to	EAGB to the TPAGE phase, $1253-1260$ evolution of a 5 $M_{\odot}$ model during the thermally pulsing asymptotic giant branch (TPAGB) phase	
	and during the core helium-burning and shell hydrogen-burning phase as a red giant, first	1260–1290 global luminosities vs time during the onset of and	
	approximation, Fig. 18.1.1, 1223 evolutionary track in the HR diagram during the core helium-burning phase, second	the first three thermal pulses of the TPAGB phase, Fig. 18.3.1, 1261 helium-burning and gravothermal minus neutrino luminosites during the second through fourth	
	mass of the convective core vs time during the core helium-burning phase, first approximation,	thermal pulses, Fig. 18.3.2, 1262 global luminosities vs time during the third therma	

Index 1483 surface luminosity vs time during the first three mass of the convective core begins to decrease. thermal pulses, Fig. 18.3.4, 1263 Structure variables and hydrogen and helium abundances are shown in the first of each pair of time variation of the mass at the base of the convective envelope and of the mass at the center figures and temperature-pressure gradients and the radiative gradient  $V_{rad}$  and its ingredients are of the hydrogen-burning shell when overshoot is shown in the second of each pair: not invoked, 1264-1265 during the first four thermal pulses, Fig. 18.3.5, (1) Figs. 11.3.17-11.3.18, 835, Vol. 1, (2) Figs. 20.2.1-20.2.2, 1347, 1264 (3) Figs. 20.2.3-20.2.4, 1348, & during the first ten thermal pulses, Fig. 18.3.6, (4) Figs. 20.2.5-20.2.6, 1349 1265 the mass of the convective core increases by almost time variation of the mass at the base of the a factor of 2 before decreasing as the central convective envelope and of the mass at the center of the hydrogen-burning shell during the tenth helium abundance becomes smaller; the model evolves toward the red giant branch in the HR through twelfth pulses, overshoot included after diagram, and the base of the convective envelope the tenth pulse, Fig. 18.3.8, 1269 increases inward in mass, dredging up material time variation of the mass at the center of the which has earlier been processed by hydrogen hydrogen profile over the course of five thermal burning and carried outward by semiconvection, pulse cycles after overshoot has been invoked. leading to a 40% increase in the surface ratio of Fig. 18.3.24, 1284 helium to hydrogen, 1350 carbon-abundance profiles vs mass just before and as the mass of the convective core decreases below just after the fifteenth helium shell flash and after its maximum mass of  $6.1M_{\odot}$ , the ratio of the subsequent dredgeup, Fig. 18.3.25, number abundances of C12 and O16 in the core 1285 decreases from approximately 1 to time variations of global luminosities over the approximately 0.6, Fig. 20.2.8, 1353 course of fifteen thermal pulse cycles, s-process nucleosynthesis occurs in the convective Figs. 18.3.26-18.3.29, 1286-1288 core as N14 ingested by the growing core is time variations of central density and temperature converted into Ne22, Ne22 captures alpha over the course of fifteen thermal pulse cycles, particles to form Mg25 and a neutron, and Fig. 18.3.30, 1289 neutrons not filtered out by capures on light time variations of surface luminosity compared isotopes are captured by heavy isotope seed with the Paczyński-Uus (PU) approximation, nuclei to form heavy s-process elements, Fig. 18.3.29, 1288 1353-1356, 1358-1359 evolution of a 25  $M_{\odot}$  model during the core evolution of a 25  $M_{\odot}$  model during core and shell helium-burning plus shell hydrogen-burning carbon-burning phases, 1359-1380 phase, 1343-1345, 1346-1359 when helium disappears over a large central core central temperature vs central density over the once comprising the convective core, the core entire period from the core hydrogen-burning contracts and heats rapidly. the number main sequence phase to the shell carbon-burning phase compared with the  $T - \rho$  relationship abundance of electron-positron pairs increases and the concomitant increase in the rate at which when  $P_{\rm rad}/P_{\rm gas} = 0.25$ . the near constancy of  $e^{-}e^{+}$  pairs produce neutrino-antineutrino pairs the slope of the evolutionary relationship which carry off energy at a huge rate, indicates that the center evolves nearly accelerating the rate of core contraction and adiabatically, Fig. 20.1.3, 1344 heating, 1359-1362 temperature vs density at the center of models of 1, contraction and heating extends to beyond the 5, and 25  $M_{\odot}$  during nuclear burning stages. carbon-helium interface and helium burning is Comparing with the lines of constant electron regnited in a shell, 1359-1361 Fermi kinetic energy over kT, it is evident that electrons at the center of the 25  $M_{\odot}$  model do carbon ignites at the center, gravothermal energy initially supplies most of the energy lost to not become significantly degenerate until after carbon burning begins, Fig. 20.1.4, neutrinos. then energy generated by 1345 carbon-burning reactions in the core supplies most of the energy lost to neutrinos, characteristics vs mass are shown at four different 1360-1362 times during the core helium-burning phase: (1) at the beginning, (2) halfway through, global luminosities generated by various energy (3) near the end while the mass of the convective sources rival the luminosity of the globular core is still increasing, and (4) near the end as the cluster  $\omega$  Cen, 1371, Table 20.3.3, 1376

1484	I	ndex
	1	
	evolution of a TPAGB model of initial mass 1 $M_{\odot}$ in response to superwind mass loss, 1397–1399 departure from the TPAGB branch in the HR diagram occurs when the mass of the hydrogen-rich envelope decreases below a critical value which is of the order of ten times the mass of the hydrogen-burning shell, 1397–1398 after termination of the superwind, evolution in the HR diagram proceeds to the blue at essentially constant luminosity along what is called a plateau branch, Fig. 21.3.1, 1398 evolution of the 0.565 $M_{\odot}$ remnant of a 1 $M_{\odot}$ model	characteristics at the center of the hydrogen-burnin shell (mass and radius location, state variables, and H-burning luminosity) at the beginning and end of the PPN phase and at six times during the white dwarf phase, Table 21.6.1, 1437 central and global characteristics at the beginning and end of the PNN phase and at six times durin the white dwarf phase, Table 21.6.2, 1447 transition from CN-cycle burning to pp-chain burning as the major nuclear burning contributo to the surface luminosity occurs between 2 × 10 yr and $10^7$ yr after the PNN phase, Fig. 21.6.6, 1437, 1443–1444; during the transition, the
	(after superwind mass loss) as the central star of an observable planetary nebula, 1398–1410, 1433, 1437 evolutionary track in the HR diagram Fig. 21.3.1	position of maximum nuclear energy generation moves from the center of the hydrogen profile to the outer portion of the profile, Fig. 21.6.7, 1438 Fig. 21.6.11, 1444
	1398 time evolution of the global nuclear burning luminosities, the surface luminosity, and the	excitation energy in a compound nucleus, 1070 experimental properties of beta decay reactions, 1009–1010
	surface temperature, Fig. 21.3.4, 1403 time evolution of state variables at the center of the hydrogen-burning shell, the radial location of the center of the shell, the hydrogen-burning luminosity, and the mass of the hydrogen-rich envelope, Fig. 21.3.13, 1410 time evolution of the surface luminosity, surface temperature, and the global hydrogen-burning	experimental Q values for electron and positron decays are related to the difference in rest mass energies of parent and daughter nuclei by $\Delta Mc^2 = Q \pm m_ec^2$ , the rest mass energy of ar electron, 984, 993 for electron decay, $\Delta Mc^2 = Q + m_ec^2$ , 984 for positron decay, $\Delta Mc^2 = Q - m_ec^2$ , 993
	gravothermal, and neutrino-antineutrino luminosities from 10 <sup>3</sup> yr before to 10 <sup>5</sup> yr after the initiation of the planetary nebula phase, Fig. 21.6.1, 1433 time evolution of the surface luminosity, surface	Fermi-Dirac distribution function, 957 Fermi, Enrico, 1011, 1022, 1074, 1420 Festa, G. C., & Ruderman, M. A., 1051 Feynman, R. P., & Gell-Mann, M., 1011 current current theory of weak interactions
	gravothermal, and neutrino-antineutrino luminosities from $10^3$ yr to $10^{10}$ yr after the initiation of the planetary nebula phase,	1013–1019 FG Sge, a born again AGB star, 1395, 1464 Fierz transformation, 1043
	Fig. 21.6.6, 1437 evolution of the $0.565M_{\odot}$ remnant of a 1 $M_{\odot}$ model (after superwind mass loss) as a white dwarf after being the central star of an observable	following helium exhaustion at the center of a star, subsequent evolution depends on the initial mass of the star, 1070–1071 in a star of initial mass in the range 2.25–8.5 $M_{\odot}$ .
	planetary nebula, 1398, 1403, 1410, 1433–1455 evolutionary track in the HR diagram, Fig. 21.3.1,	the CO core becomes electron-degenerate, 1071 in a star of initial mass in the range 8.5–10.5 $M_{\odot}$ ,
	time evolution of the global nuclear burning luminosities, the surface luminosity, and the surface temperature, Fig. 21.3.4, 1403 time evolution of state variables at the center of the	which becomes electron-degenerate, 1071 stars of initial mass larger than 10.5 $M_{\odot}$ ignite carbon before electrons in their CO cores become degenerate, 1070
	hydrogen-burning shell, the radial location of the center of the shell, the H-burning luminosity, and the mass of the hydrogen-rich envelope, Fig. 21.3.13, 1410	stars with electron-degenerate CO or ONe cores become TPAGB stars, alternately burning heliu and hydrogen in shells, ejecting their envelopes in a superwind and becoming white dwarfs,
	time evolution of the surface luminosity and temperature, the hydrogen-burning and gravothermal luminosity, and the neutrino-antineutrino luminosity. Fig. 21.6.1	10/1 Fontaine, G., & Michaud, G., 918 Fowler, W. A., & Hoyle, F., 1384 Frauenfelder, H. Bohone, R., von Goeler, F., et al.

1485		Index
	-	
	Fricke's law, 901	Heisenberg uncertainty principle, 945, 1426
	Fujimoto, M. Y., 1463	Heisenberg, W., 1426
	Fushiki, I., & Lamb, D. Q., 1091	helicity operator, 1037, 1038
		helium burning in low mass first generation stars, 1071, 1099
	gamma matrices in Dirac's theory of the electron,	helium-burning nuclear reactions, 1070–1099
	anticommutation relationships 1040	neitum-burning runaway
	avial vectors 1042	see neitum sneit flashes
	four vectors 1040–1041	helium cores of low mass red grants, 1012, 1070
	nseudoscalars 1042	1260, 1200
	scalars 1040-1041	in the electron degenrate helium core of a low m
	tensors 1042	in the electron-degenrate nemuli core of a low in
	Gamow G & Schönberg M 980	during the TDACP phase of a low mass stor
	Glashow, S. L. 1012	1175–1218
	global luminosities at several times before and during	during the TPAGE phase of an intermediate mass
	the first helium shell flash in a 1 $M_{\odot}$ TPAGB	star 1260–1200
	model Table 17.3.1 1188	Helmholtz free energy and phonons 1/26_1/20
	lessons from Table 17.3.1, 1189–1190	Herwig E 1463 1464
	global luminosities at several times during and	Herwig, F., 1405, 1404 Herwig, F. Blöcker, T. Langer, N. & Driebe, T.
	between the first two of the fifth set of thermal	1463 1464
	pulses in a 1 $M_{\odot}$ TPAGB model. Table 17.4.1.	higher order beta transitions 1000
	1195	Hikasa K et al. 1019
	lessons from Table 17.4.1 1195–1197	horizontal branch (HB) phase of a 1 Mo model:
	Glyde H R & Keech G H 1432	hydrogen burns quiescently in a shell and heli
	Goldstein H 943	burns quiescently in a convective core in which
	gradients in thermodynamic variables and the electric	electrons are not degenerate 11/9-1166
	field assuming no net flow of electrons 962–968	Hove F & Schwarzschild M 1078
	electrons are not or are only weakly degenerate	Hoyle F 1078
	962–965	Huang K 894
	electric field strength involves a temperature	Hubbard W B $973 975-976$
	gradient, 965, 968	Hubbard W B and Lampe M 975–976
	electrons are degenerate, 966–968	Hubburd, W. D., and Euripe, W., 975 976
	gravitational settling, 901	
	Green R. F. 1465	Iben, I., Jr., 973, 975, 977, 980, 998, 1003, 1009,
	GW Vir a PG1159 star 1463	1154, 1234, 1235, 1265, 1397, 1460, 1461
	6 W VII, a1 61157 Stail, 1465	Iben, I., Jr., Fujimoto, M. Y., & MacDonald, J.,
		1429
	Haft, M., Raffelt, G., & Weiss, A., 1068 Hansen, J. P., & Mazighi, R., 1432	Iben, I., Jr., Kaler, J. B., Truran, J. W., & Renzini, A 1463
	Hansen, J. P., & Torrie, G. M., & Viellefosse, P., 1432	Iben, I., Jr., & Laughlin, G., 1466–1467
	Hardy, J. C., et al., 1018–1019	Iben, I., Jr., & MacDonald, J., 918, 940, 1462, 1463
	heat capacity, definition of, 943	Iben, I., Jr., & Tuggle, R. S., 1342
	heat conduction by electrons, 941–978	Iben, I., Jr., & Tutukov, A. V., 1246, 1465
	conductive opacity, definition of, 950	initial hydrogen to helium abundance ratio in globu
	cutoff angle and the Heisenberg uncertainty	clusters, 1154
	principle, 944–945	Inman, C. L., & Ruderman, M. A., 1052
	effective opacity when both radiative and	ion contribution to the rate of gravothermal energy
	conductive flow occur, 950	generation in white dwarfs, 1441–1443,
	electrical and gravitational forces contribute	1454–1455
	comparably to balance pressure gradient forces, 952–953	$\epsilon_{\text{ions}}$ in the figures is on the assumption that ions
	electron mean free path vs scattering cross section	are in the gaseous state Fig. 21.0.4, 1433, Fig. 21.6.10, 1440, and Fig. 21.6.14, 1445
	943	11g. 21.0.10, 1440, and $11g. 21.0.14, 1443$
	elementary physics of 042 051	Fig. 21.6.18, 1440 and Fig. 21.0.14, 1445,
	role in cores of red gignts, cores of ACP store, and	1.1g. $21.0.10$ , 1449, all Fig. $21.0.20$ , 1431
	in white dworfs, 041	ions are in the solid state, Fig. 21.0.22, 1455
	in white dwarts, 941	information and an end of surface and in the Sun'
	thermal conductivity, definition of 942	interior. 89.3

	I	lidex
Itoh, N., 1068		star in consequence of core helium shell flash
Itoh, N., Haya	shi, H., Nishikawa, A., & Kohyama, Y.,	1104–1149
1068, 136	52	limiting velocity of a freely falling object and viscosity, 902
Jackson I D	1052	Lindemann, F. A., 1420
Jackson, J. D., Jauch I M &	7 Watson K M 1061	liquefaction of electron-degenerate matter,
Jauen, J. 101., 0	, wason, ix. 191., 1001	1452-1455 takes place in white dwarf models between $10^7$
Kahn, F. D., &	West, K. A., 1399	and $10^{\circ}$ yr of evolution, 1452
Kaler, J. B., 13	97, 1465	liquids and solids in white dwarfs, algorithms for
Kaler, J. B., &	Jacoby, G. H., 1396	estimating the equation of state of
Kaminisi, K.,	Arai, K., & Yoshinaga, K., 980	electron-degenerate matter, 1429-1433
Kii T. et al.	295	lithium abundance at the Sun's surface, 893
Kittel C 1/1	1	Lorentz transformation, 1029
Koehler D F	& O'Brien 1205 Fig 10.2.1 1208	luminosity-core mass relationship for a low mass r
Koenter, D. k	Weidemann V 1206	giant, eq. (18.2.8), 1246
Kocster, D., &	We man $K = 1462$	8
Koester, D., &	werner, K., 1403	
Kohyama, Y.,	1068	MacDonald, J., 1429, 1431
Kwok, S., Pur	on, C. R., & FitzGerald, P. M., 1399	Magellanic clouds, white dwarf masses vs main sequence progenitor masses demonstrate supervind mass loss 1396
Lampe, M., 97	052	Marchalz M E 072
Langmun, I., I		maniful stor evolution finale often public sympthesis
Landau, L.D.,	& Litschitz, E.M., 1431	massive star evolution imale. after nucleosynthesis
Lauritsen, 1.,	x Ajzenberg-Selove, F., 1009	has produced predominantly iron peak eleme
Lawler, T. M.,	& MacDonald, J., 1463, 1464	core collapse accelerates. multiple
Lee, T.D., 973		photodisintegrations decompose iron peak
Lee, T. D., & V	Wu, C. S., 1019	elements into alpha particles and alpha partic
Lee, T. D., & '	Yang, C. N., 1019	into neutrons and protons which capture
level widths for	r the decay of the C12 compound	electrons to become neutrons. The core become
nucleus in	the second excited state, 1082	a neutron star or black hole and the envelope
Levine, M. J.,	1026, 1051	above the collapsing core is expelled by the
Liebert, J., 140	55	transfer of momentum from neutrinos emana
Liebert, J., Do	nn, C. C., & Monet, D. G., 1466	from the core, 1389
lifetime of an	sotope experiencing a beta process in a	mean free path, definition in terms of number dens
star relati	ve to the experimental lifetime of the	and scattering cross section, 943
relevant r	rocess in a terrestial laboratory.	Melrose, D. B., Weise, J. I., & McOrist, J., 1068
982-984	986 989 991 993 995-999	melting point for solids, 1418–1420
electron dec	av in a star is inhibited by the fact that	Merrill P W 1291
decay car	not occur to occupied electron states	Mestel I. 973
983	inor occur to occupied electron states,	Mestel I & Ruderman M A 1420
lifetime of a p	sitron emitter in a star versus positron	Mire variables x 1303 1306 1307 $1/62$
doory life	time in the laboratory 002 007 008	mixing across the hydrogen carbon discontinuity
uecay inte	unite in the faboratory, 993, 997–998	formed during the third dradeour enjoyde of
position dec	ay intenness are identical, 995	the fourteenth holium shall flesh in a 5 M
electron cap	ture lifetimes when electrons are free or	the fourteenin helium shell hash in a 5 $M_{\odot}$
in a K-sn	995-999	1202 1212
electron cap	ture lifetimes when electrons are	1302–1313
degenerat	e, 999–1000	abundances in the mixed region after hydrogen
lifetimes agair	st decay of the C12 compound nucleus	burning of mixed products, Figs. 19.3.1–19.3
formed by	y Be8+alpha reactions, 1085	1302–1304
C12** again	ist gamma decay to C12*, plus $e^+\epsilon^-$	C13 abundance peak is formed in the region wh
decay to C1	2 (very large)	mixing has taken place during dredgeup,
C12* gamm	a decay to C12 does not occur	Figs. 19.3.2–19.3.3, 1304
C12** again	st decay into Be8 plus alpha particle	neutron production in the C13 abundance peak
(verv sma	11)	tenth, one third, four tenths, and halfway thro
		, ,
lifting of elect	con degeneracy in the	the fourteenth interpulse phase

1487	Index		
1487	<ul> <li>abundances in the C13 abundance peak before and after the neutron capture episode, Fig. 19.3.12, 1309</li> <li>neutron and proton capture rates in the C13 abundance peak four tenths of the way through the fourteenth interpulse phase, Fig. 19.3.13, 1313</li> <li>Mladjenović, M., 1011</li> <li>(the) moment of the linear momentum, when set equal to zero, gives the equation for bulk acceleration as the difference between the sum of gravitational and electrical forces and the pressure gradient, 900</li> <li>examining the actual forces on ions and electrons in the case of pure hydrogen when particle pressures are given by the perfect gas law, the net inward force on an electron is same as that on a proton, but the net force on an electron is almost entirely electrical while the force on a proton is half gravitational and half electrical, 911</li> <li>inserting the electrostatic field strength demanded by assuming charge neutrality, one recovers the normal pressure balance equation which makes no reference to an electric field, 902–903</li> <li>moments of the Boltzmann equation, 895–900 linear momentum moment, 898–899, 930 mass conservation moment, 906–907</li> <li>monoelemental gas in complete equilibrium, 901–906</li> <li>monoelemental surface abundances in many white dwarfs, 893, 1456</li> </ul>	products of complete neon burning are mostly <sup>16</sup> O, <sup>24</sup> M <sub>g</sub> , and <sup>28</sup> Si, Table 20.4.1, 1381 neutral currents and intermediate vector bosons, 1012 neutrino-antineutrino energy-loss rates in white dwarfs, 1437–1438, Fig. 21.6.6, 1437 neutrino-antineutrino pair production processes, 1012 1024–1033 annihilation of real electron-positron pairs, 1024–1033, 1050 bremstrahlung process, 1050–1051 photoneutrino process, 1050–1051 photoneutrino process, 1050–1051 plasma processes, 1052–1061, 1061–1068 neutrino energy-loss rates, 1001–1009 electron capture on a positron emitter, 1008–1009 electron capture on a positron stable isotope, 1001–1007 neutron-capture cross sections averaged over velocity distribution, $\sigma_{\rm KT}$ , 1294–1301 for radiative neutron-capture reactions, Tables 19.2.1a and 19.2.1b, 1296, 1297 for the <sup>14</sup> N(n,p) <sup>14</sup> C reaction, Fig. 19.2.2, 1301 neutron-capture cross section for the <sup>14</sup> N(n,p) <sup>14</sup> C reaction times the velocity as a function of the bombardment energy, Fig. 19.2.1, 1298 neutron-capture nucleosynthesis in the convective shell during the fifteenth helium shell flash in a 5 <i>M</i> <sub>☉</sub> model, 1322–1336 structure variables and number abundances of <sup>12</sup> C and <sup>4</sup> He vs mass in the primary helium-burning	
	901–906 monoelemental surface abundances in many white dwarfs, 893, 1456 Montmerle, T. & Michaud, G., 929 Muchmore, D., 918 muon decay, 1020–1024	$5 M_{\odot}$ model, 1322–1336 structure variables and number abundances of <sup>12</sup> C and <sup>4</sup> He vs mass in the primary helium-burning region 12.65 years, 1.823 years, and 2.072 days before and 1.511 years after the peak of the fifteenth helium shell flash, Figs. 19.5.1–19.5.4, 1323–1324	
	<ul> <li>N14(α, γ)F18(e<sup>+</sup>, ν)O18 and O18 (α, γ)Ne22 reaction and energy-generation rates, 1093–1094</li> <li>N14 is the major absorber of neutrons in the C13 number-abundance peak in TPAGB stars when the C13(α, n) reaction is activated, 1292</li> <li>Ne22(α, n)Mg25 reaction, 1096 reaction rate, 1096–1099 resonances, Table 16.5.1, 1097</li> <li>Ne22(α, n)Mg25 reaction is the major neutron source in the He-burning convective shell in intermediate-mass TPAGB stars during the peak of a helium shell flash, 1293, 1326–1336</li> <li>Neddermeyer, S.H., 8 Anderson, C.D., 1020 neon-burning reactions, 1380–1381 initiation by photodisintegration of Ne20 into O16 + an alpha particle which is captured by Ne20 and Mg24 to form Mg24 and Si28, respectively, 1320</li> </ul>	nucleosynthesis vs mass 1.823 years and 2.072 days before and 1.511 years after the peak of the fifteenth helium shell flash, Figs. 19.5.5–19.5.7, 1326–1327 neutron number abundance and its time rate of change vs mass, 123.64, 28.609, and 2.072 days before the peak of the fifteenth helium shell flash; neutron production is due primarily to $(\alpha, n)$ reactions on C13 being ingested by a convective shell growing in mass, Figs. 19.5.8–19.5.10, 1329–1330 neutron number abundance and its time rate of change vs mass, 9.93 and 32.59 days after the peak of the fifteenth helium shell flash; neutron production is due primarily to $(\alpha, n)$ reactions on Ne22; Ne22 is made by the reactions <sup>14</sup> N $\alpha, \gamma$ ) <sup>18</sup> F( $e^+v_e$ ) <sup>18</sup> O( $\alpha, \gamma$ ) <sup>22</sup> Ne on the N14 ingested by the convective shell before temperatures become large enough for Ne22 to	

1488		ndex
	neutron-capture nucleosynthesis in the convective shell during the fifteenth helium shell flash in a $5 M_{\odot}$ model ( <i>cont.</i> )	neutron to proton ratio in the prevailing isotope mix increases with each successive nuclear burning phase, 1388
	neutron number abundance and its time rate of change versus mass, 1.5514 years after the peak of the fifteenth helium shell flash; neutron production below the base of the convective shell is due to ( $\alpha$ , $n$ ) reactions on both Ne22 and C13; C13 is the consequence of ( $n$ , $p$ ) reactions on N14 followed by the <sup>12</sup> C( $p$ , $\gamma$ ) <sup>13</sup> N (e <sup>+</sup> $v_e$ ) <sup>13</sup> C reactions, Fig. 19.5.13, 1333	Nomoto, K., Thielmann, F., & Miyaji, 1089, 1090 number abundances, structure variables, and nuclear reaction rates of relevance to the production of s-process elements in the region traversed by th hydrogen-burning shell in a 5 $M_{\odot}$ model during the interpulse phase following the fourteenth helium shell flash, Figs. 19.4.1–19.4.9, 1313–1322
	neutron production and absorption in and below the convective shell, ten days and one month after the peak of the fifteenth helium shell flash, Figs. 19.5.14–19.5.15, 1334	carbon isotope abundances vs mass in the region behind the hydrogen-burning shell during the interpulse phase at 1720, 3522, and 5603 years after the peak of the fourteenth helium shell flosh Fig. 19.4.1, 1313, 1315
	time dependences of the conversion of <sup>1</sup> N into <sup>22</sup> Ne and of <sup>22</sup> Ne into <sup>25</sup> Mg in the convective shell during the fifteenth flash, Fig. 19.5.16, 1335	near the end of the interpulse phase, <sup>13</sup> C has been destroyed by the <sup>13</sup> C( $\alpha$ , n) <sup>16</sup> O reaction over th inner two thirds of the mass through which the hydrogen burning shell has passed and over the
	production vs time of heavy s-process elements in the convective shell as measured by the mass of neutrons captured by the heavy elements, Fig. 19.5.17, 1336	inner one third of the region, the triple alpha reaction has added significantly to the abundand of <sup>12</sup> C left behind by the advancing shell, 1314–1315
	neutron-capture nucleosynthesis in TPAGB stars and heavy s-process element production in the Universe, 1336–1338 neutron capture on <sup>56</sup> Fe and its neutron-rich progeny are the primary source of s-process elements in	structure variables and abundances of <sup>12</sup> C, <sup>13</sup> C, and <sup>14</sup> C vs mass, 3522 and 5603 years after the peak of the fourteenth helium shell flash, Figs. 19.4.2–19.4.3, 1315–1317
	stars and absorption of neutrons by <sup>14</sup> N plays a dominant role in controlling the flux of neutrons available for s-process nucleosynthesis in regions outside of the convective shell, 1215–1216, 1292	neutron number abundance and its time rate of change, abundances of <sup>13</sup> C, <sup>14</sup> C, and <sup>57</sup> Fe, and density and temperature vs mass, 3522 and 560 years after the peak of the fourteenth helium shell flash, Figs. 19.4.4–19.4.5, 1317–1310
	neutron production and capture in the convective shell of a 1 $M_{\odot}$ TPAGB model, beginning of s-process nucleosynthesis, 1214–1218	neutron and proton capture rates vs mass, 3522 years after the peak of the fourteenth helium shell flash, Fig. 19.4.6, 1319–1320
	of the eleventh set of flashes, Table 17.6.1, 1216 neutron production and capture reaction rates	number abundances of isotopes of relevance for s-process nucleosynthesis vs mass in the region between carbon-rich and hydrogen-rich matter,
	experimental, 1293–1301 Bao et al. estimates of capture rates, Tables 19.2.1a-19.2.1b, 1296–1297	3522 and 5603 years after the peak of the fourteenth helium shell flash, Figs. 19.4.7–19.4.8, 1320–1322
	neutron-production and neutron-capture nucleosynthesis in a 5 $M_{\odot}$ model during the TPAGB phase, 1291–1336	s-process nucleosynthesis vs mass in the vicinit of the hydrogen-burning shell, 3522 years after the peak of the fourteenth helium shell flash,
	neutron-production and neutron-capture rates, 1293–1302 neutron-production and neutron-capture	Fig. 19.4.9, 1320, 1322 number of electrons in a typical plasmon, 1064–1065
	nucleosynthesis in a 25 $M_{\odot}$ model during the core helium-burning phase, 1353–1359 neutron-rich member of an isotope increases in	$O16(\alpha, \gamma)$ Ne20 reaction and energy-generation rates
	abundance with increasing temperature, 1388 neutron sources of primary importance in stars are the ${}^{13}C(\alpha, n)O$ and the ${}^{22}Ne(\alpha, n){}^{25}Mg$ reactions,	<ul> <li>OFO(α, γ) NO20 reaction and energy-generation rates</li> <li>1092–1093</li> <li>OH-IR stars, 1396</li> <li>ω Cen, most luminous globular cluster in our Galaxy</li> </ul>

M	loi	eı	nto	orr	nat	10r	1

1489	Index			
	Öpik, E., J., 1078 Orear, J., Rosenfeld, A. H., & Schluter, R. A., 1074 oscillations of ions in a solid and the melting point, 1410–1411, 1418–1420 Osterbrock, D. E., 1397	relative abundances of isotopes in equilibrium with respect to radiative capture and photodisintegration reactions, 1387–1388 photodisintegration of a nucleus with the emission of an alpha particle, 1380–1381		
	oxygen-burning reactions, 1381–1384 cross sections and branching ratios for various reactions vs center of mass energy, Fig. 20.4.1,	example: ${}^{20}\text{Ne}(\gamma, \alpha){}^{10}\text{O}(\alpha, \gamma){}^{20}\text{Ne}$ , 1380–1381; relative abundances when reactions are in equilibrium, 1380–1381		
	cross sections for various reactions at 7 MeV center of mass energy, Table 20.4.2, 1382 branching ratios for various reactions at 7.5 MeV center of mass energy, Table 20.4.3, 1383 products of complete oxygen burning are mostly silicon and sulfur, Table 20.4.4, 1384	photoneutrino energy-ioss process, 1051 physical processes of importance in a low mass stellar model (after envelope ejection in a superwind, evolution as the central star of a planetary nebula and evolution as a white dwarf) at different positions in the HR diagram, Fig. 21.7.2, 1459		
	1071 oxygen in the Universe is from massive stars,	plane parallel atmosphere in a constant gravitational field at constant temperature, 901–906		
	oxygen-neon cores of massive AGB stars, 1012–1013	for pure hydrogen, the scale height for protons is twice the scale height for neutral hydrogen, 905 for pure helium, no simple solution exists, 905–906		
	Paczyñski, B., 1202, 1396	plasma frequency, 1052, 1059–1061		
	Paczyński-Uus (PU) relationship between the surface	plasma neutrino energy-loss rates, 1066–1067		
	luminosity of a TPAGB model and the mass at	plasma oscillations, 1052–1068		
	the center of the hydrogen profile, eq. (1/.4.1),	in classical physics, 1052–1061		
	1202	dispersion relationship for longitudinal		
	luminosity during TPACB thermal pulses	oscillations, 1057, 1061		
	Fig. 17.4.15, 1202	dispersion relationship for transverse waves,		
	for intermediate mass models, it is an asymptote which is approached near the end of the	plasma frequency, non-relativistic, degenerate		
	quiescent hydrogen-burning portion of the TPAGB phase after many pulses, Fig. 18.3.29,	electrons, 1059–1061 plasma frequency, non-relativistic electrons, 1052, 1059–1061		
	1288 partial pressure 012 013 031	phase and group velocities, 1058		
	Patterson I R Winkler H & Zaidens C S	in quantum physics, 1061–1068		
	1363	both transverse and longitudinal plasmons have		
	Pauli spin matrices, 1034	an effective mass given by $h\omega_p/c^2$ , where		
	Pauli, W. 1011	$\omega_p$ is the plasma frequency, 1012, 1062		
	Perinotto, M., 1399 Perkins, D. H., 1020	number density of longitudinal plasmons,		
	Petrosian, V., Beaudet, G., & Salpeter, E. E., 1051 PG1159 stars, hot central stars of planetary nebulae	number density of transverse plasmons,		
	with exotic, hydrogen-deficient spectra, 1395,	1062–1063, 1065		
	1463	plasmons as bosons, 1012, 1062		
	phase and group velocities of plasmons, 1058	rates of decay into neutrino-antineutrino pairs		
	phase space in seven dimensions, 895–896	and associated energy-loss rates, 1066–1068		
	phonons, zero point energy, Helmholtz free energy, and equation of state 1426–1429	transverse plasmons as photons with an effective mass. 1062		
	photodisintegration of a nucleus with the emission of	plasmons, transverse and longitudinal, 1061–1068		
	a proton, 1366–1367	effective masses are given by $\hbar\omega_p/c^2$ , where $\omega_p$ is		
	derivation of a theoretical disintegration rate,	the plasma frequency, 1012, 1062		
	1366–1367	rates of neutrino-antineutrino energy loss due to,		
	example: N13, a beta unstable nucleus which can	1066–1068		
	experience a $(\gamma, p)$ reaction to become C12,	PNN (planetary nebula nucleus), 1397-1410		
	1367	see central star of a planetary nebula		

1490		ndex	
	Poisson's equation, and its solution in	probability density for electrons and positrons,	
	electron-degenerate matter for the electrical	1039-1040	
	approximation that the electron Fermi energy	production of carbon in metal-free stars 1070	
	plus the potential are constant in the	1099	
	Wigner–Seitz sphere, 1420–1426		
	the general solution for static ions is a screened		
	potential which falls off inversely with the	quiescent helium burning in a convective core,	
	distance and has a screening radius which is	1149-1167, 1220-1242, 1340-1359	
	related to the radius of the Wigner-Seitz sphere	In a 1 $M_{\odot}$ model star, 1149–1107	
	through the density and the Fermi energy,	in a 25 $M_{\odot}$ model star, 1220–1242	
	1421–1425	quiescent helium burning in a shell, 1166–1171.	
	phonons in this potential propagate with a	1242–1253, 1359–1380	
	frequency related to the ion plasma frequency	in a 1 $M_{\odot}$ model star, 1166–1171	
	and the screening radius, 1423–1425	in a 5 $M_{\odot}$ model star, 1242–1253	
	transverse phonons propagate with a frequency	in a 25 $M_{\odot}$ model star, 1359–1380	
	proportional to the ion plasma frequency,		
	1425	radiative temperature-pressure gradient $V_{rad}$ during	
	amplitude to the square of the radius of the	the core helium-burning phase, 1157–1161,	
	Wigner-Seitz sphere equal to 1/36 provides an	1228–1231	
	estimate of $\Gamma$ , the ratio of the ion-electron	in a 1 $M_{\odot}$ model, 1157–1161	
	electrostatic binding energy to kT and therefore	in a 5 $M_{\odot}$ model, 1228–1231	
	an estimate of the melting temperature, 1426,	$V_{\rm rad}$ is the product of 3 factors, $\kappa$ , $L/M$ , and	
	Table 21.4.3, 1422	$P/P_{\rm rad}$ , 1157, 1231	
	planetary nebula (PN), 1393-1403	$v_{rad}$ at the edge of a helium-burning convective	
	formation, 1393–1394, 1395–1399	Fig 17.2.14 1160 Fig 17.2.17 1162	
	illumination mechanism, 1399–1400	Figs. 18.1.9–18.1.11, 1229–1231	
	lifetime, 1400–1403	consequence is the semiperiodic appearance of a	
	shaping by a hot wind from the central star, 1399	convective shell above the convective core,	
	planetary nebula nucleus (PNN), central star star of a	followed by a merger with the convective core,	
	Planck distribution of photon energy vs $hu/kT$ for a	leading to an oscillatory variation in the mass of	
	black body. Fig. 21.3.2, 1400	the convective core, Fig. 17.2.6, 1155,	
	fraction of photons and fraction of energy emitted	Fig. 18.1.7, 1228, and Fig. 18.18, 1229	
	in the form of photons with enough energy to	radius-core mass relationship for a low mass red gia	
	ionize hydrogen, Fig. 21.3.3, 1402	ram pressure the product of the bulk linear	
	plasma frequency, for ions and for electrons,	momentum density and the bulk velocity.	
	1416	899–900, 906–907	
	plateau branch, path in the HR diagram from red to	reactions through resonant tails (wings), 1061,	
	blue at nearly constant luminosity traced by the	1086–1091	
	theoretical models of such a star. Fig. 21.3.1	Renzini, A., 1396	
	1398	resistance coefficients, 894–895, 913, 915–918, 920	
	Pontecorvo, B., 1052	as inverses of diffusion coefficients, 921	
	positron decay and electron capture on a positron	effect of ion-ion collisions on the Boltzmann	
	emitter, 993–1001	transport equations, 915–918	
	general considerations, 993-995	resonant nuclear reactions, 1072–1086	
	electrons not degenerate, 995–999	resonant nuclear reaction cross sections, 1070, 1075	
	electrons degenerate, 999–1001	1078	
	example of N13 + $e^+ \rightarrow$ C13 + $\nu_e$ , Table 14.6.1, 1000	derivation of the Breit-Wigner cross section, 1072–1076	
	Pottash, S. R., 1396	Ritossa, C., Iben, I. Jr., & García-Berro, E., 980, 101	
	pressure balance, 904, 909, 910	1393, 1465	
	equation for, 904, 909, 910	Ritus, V. I., 1053	

Index 1491 r(rapid)-process nucleosynthesis; intervals between hydrogen and helium abundance profiles in a neutron captures are short compared with 25  $M_{\odot}$  model after the dredge-up episode has been completed, Fig. 20.3.1, 1360 beta-decay lifetimes, 1291 Rutherford nuclear atom, 1418 the surface He/H abundance ratio has been enhanced by 40%, 1350 Shapiro, S. L., & Teukolsky, S. A., 1420, 1423 Saha equations for elements of one species, 904, silicon-burning reactions, 1384-1385 905-906, 925-928 products of silicon burning, are mostly <sup>54</sup>Fe and for pure helium, 905-906 <sup>56</sup>Fe, Table 20.4.5, 1384 for pure hydrogen, 904 Sion, E. M., & Liebert, J., 1465 for iron isotopes, 925-928 Slattery, W. L., Doolen, G. D., & DeWitt, H. E., Saha equation for equilibrium of two isotopes 1430-1431 connected by  $(\gamma, p)$  and  $(p, \gamma)$  reactions, 1366 Solar convective envelope, characteristics at base of, Saha equation for equilibrium of two isotopes Table 12.9.1, 929 connected by  $(\gamma, \alpha)$  and  $(\alpha, \gamma)$  reactions, 1387 Saha equations for equilibrium of two isotopes solidification occurs in electron-degenerate matter connected by  $(\alpha, p)$  and  $(p, \alpha)$  reactions, 1386 when  $\Gamma$  increases to 150–250, 1426, theoretical relationship between forward and Table 21.4.3, 1422 backward reaction rates, screening included, see eq. (21.6.16), 1452, for definition of  $\Gamma$ 1387 begins at the center in white dwarfs after Sakurai's object, a born again AGB star, 1464 approximately  $2 \times 10^9$  yr of evolution and Salam, A., 1012, 1362 moves through most of the interior over the next Salpeter, E. E., 1078, 1415  $6 \times 10^9$  yr of evolution, 1455, Fig. 21.6.23, Salpeter mass function, 1467 1455 scale heights in a plane parallel atmosphere at solids and liquids in white dwarfs, algorithms for constant temperature, 901, 904, 906 estimating the equation of state, scattering cross section and thermal conduction, 1429-1433 943-947 Spinka, H., & Winkler, H., 1381 cross section invoking a maximum impact spinors, 1035, 1036, 1038 parameter equal to distances between adjacent s-process element production in the Universe by particles, 944-945 TAGB stars, summary, 1336-1338 cross section invoking the Heisenberg uncertainty s-process nucleosynthesis, history, 1291-1292 principle, 945 s-process nucleosynthesis in a 1  $M_{\odot}$  TPAGB model, cross section in the electron-screening 1214-1218 approximation, 945-947 during the interpulse phase, in the region vacated ratios of approximate cross sections, 947 by the hydrogen-burning shell, most CNO estimates of conductivity under electron-degenerate isotopes are converted into N14, C13 is produced and non-degenerate conditions, 948-951 in equilibrium with respect to C12 and then Schönberner, D., 1396-1397 partially converted into O16 plus a neutron by second dredgeup process, matter processed through the C12( $\alpha$ , *n*)O16 reaction, 1215–1216 complete hydrogen burning is carried into the C13 and N14 are ingested by the convective shell convective envelope during the EAGB phase, during a helium shell flash, N14 is converted in 1250-1252 the shell into O18 and then into Ne22, while C13 in a 5 M<sub>☉</sub> model star, 1250–1252 captures alpha particles and releases neutrons to Seeger, P. A., Fowler, W. A., & Clayton, 1291 semiconvection during the main sequence phase and form O16, 1216-1218 during the shell flash, very little Ne22 is burned, but inward motion of the base of the convective C13 is completely burned, producing one envelope during and after the exhaustion of central helium leads to a substantial increase in neutron for every seed Fe56 nucleus, 1218 the ratio of helium to hydrogen in the convective as pulse strength increases, the base of the envelope of a massive star, Fig. 20.2.3, 1348, convective envelope will eventually penetrate the Fig. 20.2.5, 1349, Fig. 20.3.1, 1360, 1350 C12 layer left behind by the receding convective abundance profiles in a 25  $M_{\odot}$  model near the end shell, hydrogen burning at the beginning of the of the core helium-burning phase, Fig. 20.2.3, next interpulse phase will produce a spike in the 1348 C13 abundance. Injestion of this spike during the abundance profiles in a 25  $M_{\odot}$  model when central next shell flash will produce s-process elements helium is almost gone, Fig. 20.2.5, 1349 in interesting amounts, 1218

Index 1492 s-process nucleosynthesis in a 5  $M_{\odot}$  TPAGB model, direct evidence for a superwind are mass loss rates 1291-1336 estimated from the spectra of Mira variables and formation of a  ${}^{13}C$  peak and neutron production OH-IR stars, 1396 and capture in the peak, 1302-1313 indirect evidence for a superwind is the presence in clusters of white dwarfs of mass comparable to nucleosynthesis during the quiescent the mass of the CO core of AGB stars in the hydrogen-burning phase, 1313-1322 nucleosynthesis in the convective shell, 1322-1336 clusters, 1395-1396 surface abundances in old white dwarfs as influenced s(slow)-process nucleosynthesis: intervals between by where in the thermal pulse cycle the precursor neutron captures are long compared with TPAGB star leaves the TPAGB, beta-decay lifetimes, 1291 1460-1464 s-process nucleosynthesis in the convective core of a final helium shell flash in the compact, hot remnant 25  $M_{\odot}$  core helium-burning model, of a former TPAGB star and the born again AGB 1353-1359 phenomenon, 1463 number abundances of isotopes in and left behind evolutionary track of a low mass model which by the shrinking convective core of the near the experiences a helium shell flash shortly after end of the core helium-burning phase are leaving the TPAGB and is subjected to mass loss evidence of s-process nucleosynthesis. by a hot stellar wind at high surface approximately one quarter of the <sup>22</sup>Ne in the temperatures. the model develops first a convective core (descended from the set of CNO hydrogen-free and then a carbon-rich surface, elements present at stellar birth) has been converted into <sup>25</sup>Mg. The neutrons released by  $(\alpha, n)$  captures on <sup>22</sup>Ne participate in s-process Fig. 21.8.1, 1461 Svartholm, N., 1025 nucleosynthesis, Fig. 20.2.8, 1353 conversion of the original CNO elements into N14, technetium, an element all isotopes of which are beta N14 into Ne22, and Ne22 into Mg25 and unstable, 1291 neutrons is detailed by entries in Table 20.2.1, discovered by Paul Merrill in spectra of red giants 1354. one out of every 10 neutrons released known as S stars, 1291 contributes to heavy element s-process lifetime of longest-lived isotope, <sup>99</sup>Tc, is 211,000 nucleosynthesis, 1355 years, 1291 rates of neutron production and neutron capture on presence in spectra of S-stars is evidence for various isotopes at two positions in the neutron-capture nucleosynthesis during the AGB convective core demonstrate that s-process phase, 1291-1293 nucleosynthesis is concentrated near the center terminal evolution of low and intermediate mass stars, of the core, Table 20.2.2, 1356 1393-1469 analysis of number abundances in the region thermal conductivity, definition of, 942 vacated by convection after helium-burning at estimates of, 943, 948-951 the center has been completed suggests that the see conductivity, thermal enhancement of heavy s-process isotopes is 60% thermalization of positrons by Compton scattering, of the maximum possible enhancement, 994 Fig. 20.2.11, 1358, and discussion, 1356, thermally pulsing asymptotic giant branch (TPAGB) 1358-1359 phase for a 1  $M_{\odot}$  model, 1171–1218 Spulak, R. G., Jr., 980 first helium shell flash, 1171-1190 stability of an isotope against electron capture or global luminosities during the first flash, Table decay switches at large enough densities, 17.3.1, 1188 979 global luminosities during and between the first two example of N14 and C14, 979-980, 1003 of the fifth set of thermal pulses, Table 17.4.1, Stokes, G. G., 902 1195 Stokes' law for the force on a body moving in a CN-cycle reactions dominate pp-chain reactions in viscous medium, 902 contributing to the luminosity during quiescent structure variables and abundances vs mass near the hydrogen-burning phases, 1205 hydogen-burning shell in a 5  $M_{\odot}$  model 626 duration of a thermal pulse episode is years after the peak of the fourteenth helium approximately a quarter of the interval between shell flash, Fig. 19.3.4, 1305, see also successive episodes, 1192 Fig. 19.3.3, 1304 helium burning in the convective shell during a superwind ejection of the envelope of a TPAGB star, flash is incomplete, mostly carbon and hardly 1395-1397, 1397-1399 any oxygen being produced, 1209

175		
	increase in the mass of the helium-exhausted core is	TPAGB stars are the major contributors of s-process
	responsible for the increase in pulse strength	elements in the Universe, 1336–1338
	with each successive pulse, 1209	TPAGB (thermally pulsing AGB) star, an AGB star
	increase in pulse strength leads to storage of more	which burns helium and hydrogen alternately in
	gravothermal energy during a pulse, a larger	shells, 1103, 1175–1214, 1260–1290,
	luminosity at the base of the convective envelope	1393–1393
	after a flash dies down, a greater extension	experiences acoustical pulsations like those
	inward in mass at the base of the convective	envelope in a superwind and becomes a white
	matter which has experienced the conversion of	dwarf 1393–1395
	helium into carbon 1209–1210	a 1 $M_{\odot}$ model 1175–1214
	observed fact that many TPAGB stars are carbon	a 5 $M_{\odot}$ model, 1260–1290
	stars demonstrates that dredgeup occurs and that	see thermally pulsing AGB stars
	TPAGB stars are responsible for carbon in the	triple alpha process,
	interstellar medium, 1210	classical reaction rate, 1078–1086
	neutron production and capture in helium-burning	energy levels in nuclei involved in the triple alpha
	regions, 1214–1218	process, Fig. 16.2.1, 1079
	number abundance changes determined by nuclear	proceeds through two resonant reactions involving
	burning, convective mixing, and dredgeup,	the formation of compound nuclei, 1070, 1080,
	1206–1214	1081
	systematics of thermal pulses along the TPAGB,	cross section for the formation of the Be8
	1191–1206	compound nucleus, 1080
	thermal pulse cycle in a TPAGB star, qualitative,	cross section for the formation of the C12
	1221–1222	compound nucleus, 1082
	a helium-burning runaway ensues when the mass of	rate of energy generation by, 1086
	helium deposited by the hydrogen-burning shell	reaction rate at low temperatures, 1086–1091
	reaches a critical value	Iruran, J. W., Cameron, A. G. W., & Gilbert, A. A.,
	nuclear energy released is stored as gravothermal	1384 Texterial V N 1052
	energy	1 sytovicii, v. IN., 1052
	stored gravothermal energy leaks out, causing	
	matter in and above the hydrogen-helium (H-He)	Urca neutrino-antineutrino energy-loss rates,
	hudrogen huming rate is dramatically reduced	1001–1004
	hydrogen-burning rate is dramatically reduced	maximum rates as a function of temperature, 1002,
	H He interface, which heats up until H burning is	1003, 1004
	resurrected	maximum rates for selected Urca pairs at
	helium hurning dies out hydrogen continues to	carbon-burning temperatures, Table 14.7.1,
	burn quiescently until the mass of helium	1003
	deposited by the hydrogen-burning shell reaches	Urca pairs, 980, 984, Table 14.7.1, 1003
	a critical value	Urca process, 980, 983–984, 1001–1004
	third dredgeup process in a 5 $M_{\odot}$ TPAGB model	tharacteristics of several Orca pairs, Table 14./.1,
	matter processed through partial helium burning	1005
	is carried into the convective envelope after a	stars 980
	helium shell flash, 1260-1290	important in carbon-oxygen core of an accreting
	see dredge-up (third)	white dwarf of mass near the Chandrasekhar
	Thomas-Fermi model of the atom, application to the	limit 980
	transition beween the solid and liquid states in	important in stars of initial mass $\sim 8.5-10.5 M_{\odot}$ as
	electron-degenerate matter,	their CO cores are converted into ONe cores
	1420–1426	during the AGB phase, 980
	Thomas, J., Chen, Y. T., Hinds, S., Meredith, D., &	nature of the process, 980, 983–984, 1001–1004
	Olson, M., 1381, 1382	Uus, U., 1202
	Thomas, L. H., 1420	
	Thomson, J. J., 1418	
	I nomson plumb pudding model of the atom,	Vous Aql, a born again AGB star, 1464
	1418 Tankas I. & Lanamurin I. 1052	v-A formulation of weak interaction theory, 1011,
	IONKAS, L., & Langmuir, L. 1052	1042-1043

1494 Index Van Horn, H. M., & Weidemann, V., 940 experimental data base shows that vector and axial viscosity and the limiting velocity of a freely falling vector terms dominate, giving rise to the V-A object, 902 hypothesis, 1017 selection rules for the two types of transition are zero parity change and zero and unity spin Watson, K. M., & Jauch, J. M., 1061 change, respectively, 1017 wave function for an electron or positron which takes adopting the V-A hypothesis with two different into account the Coulomb interaction with the coupling constants, experimental properties of nucleus, 981, 993 the O14  $\rightarrow$  N14 +  $e^+$  + neutrino and the weak interaction induced neutrino-antineutrino  $n \rightarrow p + e^- +$ anti-neutrino reactions suggest production processes, 1050-1052  $g_0 \sim 1.44 \times 10^{-49} \text{ erg cm}^3 \text{ and } g_1 \sim 1.25g_0$ , history and nature of, 1050-1052 1017-1018 initial calculations, 1052 upper limits on the vector coupling constant from 8 qualitative temperature and density dependences of superallowed nuclear beta decays give a mean electron-positron pair annihilation process, value of  $g_0 \sim 1.53 \times 10^{-49}$  erg, Table 15.1.2, 1050 1018 photoneutrino, bremstrahlung, and plasma more sophisticated analysis taking into account the processes require passage through intermediate finite size of the nuclear charge distribution and states involving interaction with the the distribution of the orbital electron charge electromagnetic field, 1050-1051 suggest  $g_0 \sim 1.42 \times 10^{-49}$  erg cm<sup>3</sup> and weak interaction theory, abbreviated version  $g_1 \sim 1.28 g_0, 1018 - 1019$ applicable when reactions involve nuclei for yet more sophisticated treatments including more which experimental lifetimes are available, experimental constraints suggest 980-984  $g_0 \sim 1.425 \times 10^{-49} \text{ erg cm}^3 \text{ and } g_1 \sim 1.79 g_0$ , theoretical decay probability, 982-983 1019 theoretical differential transition probability, prediction (Lee & Yang) and discovery 980-981 (Frauenfelder et al.) that leptons are emitted with theoretical capture probability, 983-984 opposite helicities leads to the minus sign in the transition probabilities in the laboratory, 982, 993 V-A theory, 1019 transition probabilities in a star, 983-984, 986-987, product of lepton and muon currents leads to 989, 993-999 predictions concerning muon decay, wave functions for leptons, 981, 993 1020-1024 electron decay, 981 axial vector and vector coupling constants for muon positron decay, 984 decay have the same absolute value, weak interaction theory in the nuclear context, 1024 historical, 1013-1019 axial vector coupling constant for nuclear beta Fermi's original nuclear beta decay theory, 1011 decay reactions larger than for lepton decay Feynman-Gell-Mann charged-current extention of reactions because of quark-pion effects in nuclei, the Fermi theory, 1011, 1013-1019 1024 a current, a Hamiltonian, and a weak interaction Weinberg, S., 1012, 1362 coupling constant, 1013-1015 Weinberg-Salam-Glashow neutral current extention of products of nucleon and lepton currents in the Fevnman-Gell-Mann current-current theory of current-current Hamiltonian produce nuclear weak interactions, 1012, 1071 beta-decay reactions, 1014 Werner, K., 1463 decay probability and lifetime, 1014-1015 Werner, K., & Herwig, F., 1463 dimensionless constants related to the assumed Weyman, R., 929 coupling constant, 1015 white dwarf evolution, example of a 0.565  $M_{\odot}$ coupling constant as a function of an experimental lifetime and a theoretical nuclear matrix element, remnant of a 1  $M_{\odot}$  TPAGB model after a superwind phase, 1433-1456 relevant for neutron decay, 1015 evolutionary track in the HR diagram, Fig. 21.3.1, characteristics of twelve superallowed transitions and additional estimates of the assumed single 1398, Fig. 21.7.2, 1459 coupling constant, Table 15.1.1, 1016 time evolution of the surface luminosity and general considerations permit five relativistically temperature, the hydrogen-burning and invariant terms in the Hamiltonian, each with a gravothermal luminosity, and the different coupling constant: scalar, pseudoscalar, neutrino-antineutrino luminosity, Fig. 21.6.1, vector, axial vector, and tensor, 1017, 1040-1042 1433, Fig. 21.6.6, 1437

1495	I	lidex
	time evolution of the global nuclear burning luminosities, the surface luminosity, and the surface temperature, Fig. 21.3.4, 1403	white dwarf precursor evolution, 1395–1410 a superwind ejects most of the hydrogen-rich envelope of a TPAGB star, 1395–1397
	time evolution of state variables at the center of the hydrogen-burning shell, the radial location of the center of the shell, the H-burning luminosity, and the mass of the hydrogen-rich envelope, Fig. 21.3 13, 1410	remnant evolves at nearly constant luminosity from the TPAGB branch to the blue of the main sequence, along a plateau branch, 1397–1398, Fig. 21.3.1, 1398
	<ul> <li>time evolution of the surface luminosity and temperature, the hydrogen-burning and gravothermal luminosity, and the neutrino-antineutrino luminosity during the PNN phase and the early white dwarf phase, Fig. 21.6.1, 1433</li> <li>time evolution of surface luminosity, surface temperature, and global hydrogen-burning,</li> </ul>	photoionization of hydrogen by photons from the remnant with energies greater than the ionization potential of hydrogen, excitation of low-lying atomic levels by collisions between free electrons and ions, and subsequent radiative transitions between the low-lying atomic levels produces visible light, 1399–1400 luminosity of remnant during its tenure as the
	gravothermal, and neutrino-antineutrino luminosities from $10^3$ yr to $10^{10}$ yr after the initiation of the planetary nebula phase, Fig. 21.6.6, 1437	central star of a planetary nebula is due to hydrogen-burning in a shell at the base of a hydrogen-rich envelope of decreasing mass, an example being given by Fig. 21.3.4, 1403.
	characteristics at the center of the hydrogen-burning shell (mass and radius location, state variables, and H-burning luminosity) and end of the PPN phase and at six times during the white dwarf phase, Table 21.6.1, 1437 central and global characteristics at the beginning and end of the PNN phase and at six times during	Fig. 21.3.13, 1410, and Fig. 21.6.1, 1433 as the mass of the hydrogen-rich envelope decreases, temperatures in the hydrogen-burning shell approach the relatively low and constant temperature at the surface and, in consequence, the hydrogen-burning luminosity decreases until
	the white dwarf phase, Table 21.6.2, 1447 hydrogen burning contributes to the surface luminosity during early evolution, Table 21.6.1, Fig. 21.6.6, 1437	the release of gravothermal energy in outer layers of the remnant supply most of the energy emitted at the surface, 1409–1410
	cooling by heavy ions becomes the major contributor to surface luminosity during late stages of evolution, 21.53–21.60, Fig. 21.7.2, 1459	Wigner, E., & Seitz, F., 1411 Wigner-Seitz sphere, Coulomb forces between electrons and ions, 1411–1412
	contribution of electrons to cooling relative to that of ions is proportional to $kT/\epsilon_{\text{Fermi}}$ times $Y_e/Y_{\text{ions}}$ , where $Y_e$ and $Y_{\text{ions}}$ are the number abundances of electrons and ions, respectively, 1443	<ul> <li>Willson, L. A., &amp; Hill, S. J., 1397</li> <li>Winget, D. E., et al., 1466, 1467</li> <li>Wood, P.R., &amp; Faulkner, D.J., 1397</li> <li>Wu, CS., Ambler, E., Hayward, R. W., Hoppes, D. D., &amp; Hudson, R. P., 1019</li> </ul>
	diffusion in surface layers leads to a monoelemental spectrum after several times 10 <sup>8</sup> yr of cooling, 1456–1460, Fig. 21.7.1, 1458	Wu, CS., Barnes, C. A., 1381–1383
	transition from gaseous to liquid state in the interior takes place between 10 <sup>7</sup> and 10 <sup>8</sup> yr of cooling, 1455	ZAHB (zero age horizontal branch) is the location in the HR diagram of low mass stars just beginning the core helium-burning phase,
	transition from liquid to solid state tukes place between $2 - 9 \times 10^9$ yr of cooling, 1455 white dwarf number-luminosity distributions and the	1146–1151 Zaidi, M. H., 1052 zero age horizontal branch (ZAHB) model of mass
	age of the Galactic disk, 1464–1469 theoretical and observed luminosity functions for white dwarfs in our Galaxy, Fig. 21,9,1, 1465	$1 M_{\odot}$ , 1149–1151 zero point energy, Helmholtz free energy, and phonons, 1426–1429