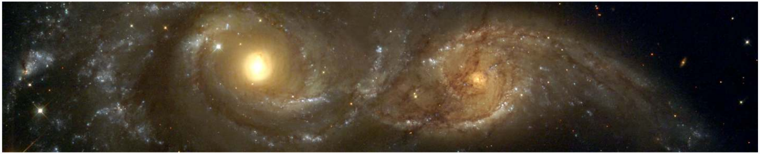

Physics of Compact Objects
Fall 2023

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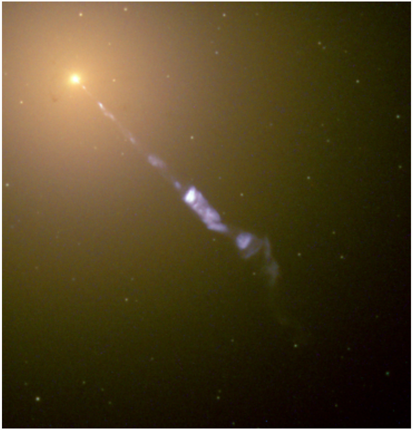
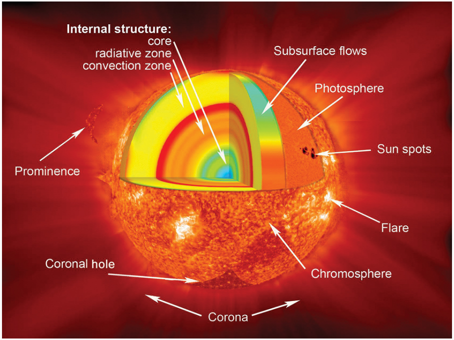


Figure 1: M87 Jet.

The Sun

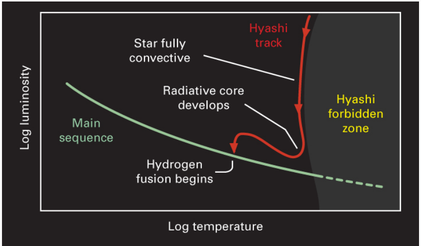
- Nuclear burning core, 15 MK
- Radiative zone
- Convective zone, 10^4K
- Photosphere, 5800-4200 K
- Chromosphere, 10^4K
- Corona, $>$ MK
- Hydrostatic Balance
- Radiation, interior to surface, random walk, photons 7000 yrs.
- Diffusion, leads to $L \sim M^3$.

How did the sun get to this point?

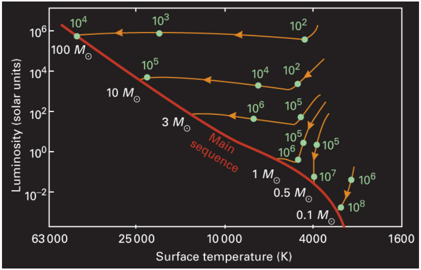


Protostar (Cloud) Evolution

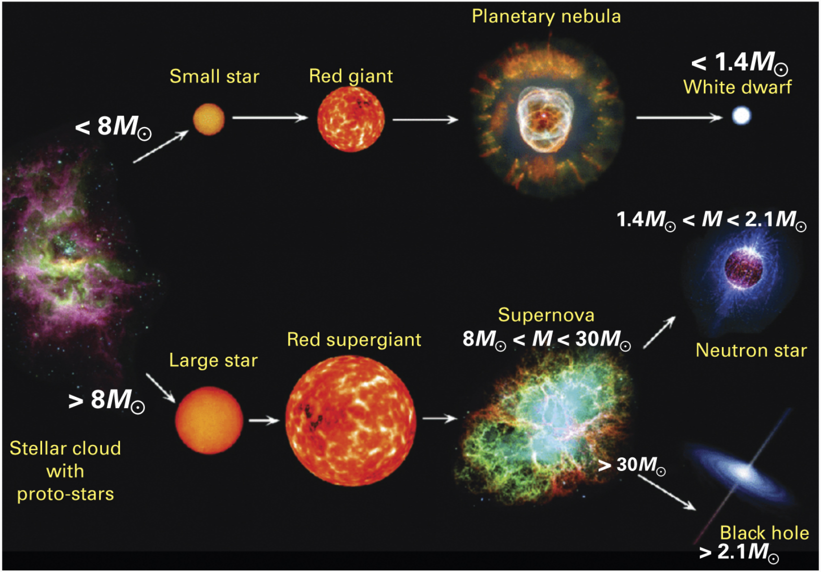
- Mass contracts from cloud.
- Main Sequence: R decreases, T increases, L ≈ const.
- $M \geq M_\odot$, horizontal track, stops at main sequence.
- When core T high, H-fusion leads.
- High L, large R. Conracts vertically, Hyashi track.
- When $L \sim M^3$, becomes radiative, left turn on Henyey track.
- When H delpeted, backtracks to cool red giant.



Hyashi tracks and the Hyashi forbidden zone

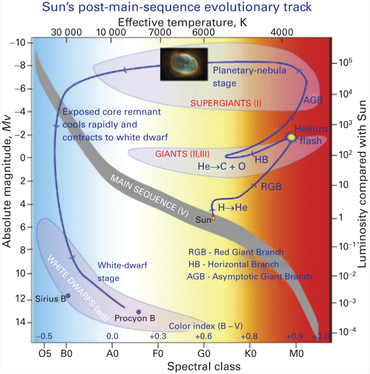


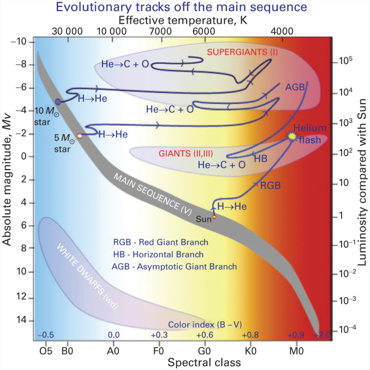
Evolution to Final States - Fig. 19.1



Post Main Sequence Evolution - Fig. 19.2

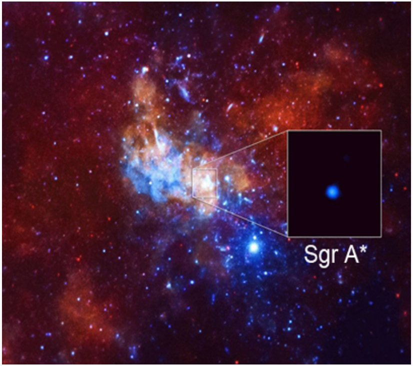
H-R diagrams showing evolution for $M = 1, 5, 10\ M_\odot$.





Compact Astrophysical Objects

- Endpoints of stellar evolution.
  - White dwarfs.
  - Neutron stars.
  - Black holes.
- Constituents of galaxies
- Extreme Objects at centers of
  - Milky Way - Sagittarius A* - $4.1 \times 10^6 M_\odot$,
  - M87* in Virgo Cluster - $6.5 \times 10^9 M_\odot$.
- Detection modes
  - Neutron stars, BHs - radio, X-ray emissions.
  - White dwarfs - optical.



https://www.nasa.gov/sites/default/files/chandra20140105.jpg

Black Holes

- 1783 - John Michell
  - applied gravity to corpuscules.
  - predicted dark stars.
- 1796 - Pierre-Simon Laplace
  - predicted point of no return.
- 1915 - Albert Einstein - GR.
- 1916 - Karl Schwarschild
  - Spherical symmetry.
- 1939 - J. Robert Oppenheimer and Hartland Snyder - Stellar collapse.
- 1939 - Einstein denied.
- 1967 - John Wheeler coined name.
- 1970 C.V. Vishveshwara.
  - Stability of Schwarzschild BH.
  - Quasinormal modes, ring down.

Figure 2: M87* - 2019 EHT Picture.

- 1964, 1971 - Cygnus X-1
  - 6070 lyr, 14.8$M_\odot$.
  - $R_s = 44$ km. [1$M_\odot \rightarrow$ 2.95 km]
- List of Black Holes

Black Holes Have No Hair

- Oppenheimer and Snyder assumed
  - Perfectly spherical.
  - Non-rotating.
  - No imperfections.
  - Controversial.
- 1964 - Roger Penrose
  If matter has a positive energy-density, a trapped surface has a singularity.
- 1966 - Stephen Hawking
  The Singularity Theorem is for the whole universe, and works backwards in time.
- 1967 - Werner Israel - 1^{st} Schwarzschild.
- 1972 - Jacob Bekenstein (via Wheeler)
  - "Black holes have no hair."
  - just mass, angular momentum, charge.

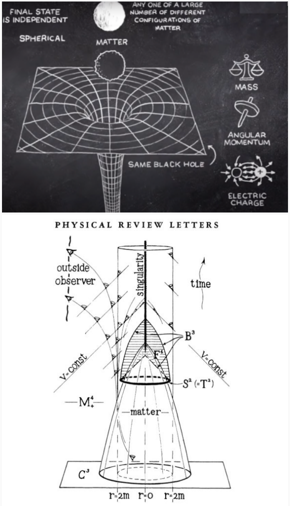


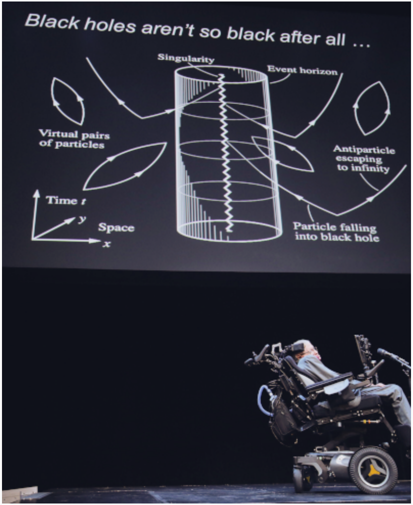
Figure 3: Video.

Black Hole Thermodynamics

- 1972 - Jacob Bekenstein
  Black holes should have entropy.
- 1974 - Stephen Hawking
  - They have a temperature.
  - And emit Hawking radiation.

$$S = \frac{kA}{4\ell_p^2}, \quad kT = \frac{hc^3}{16\pi^2 GM}.$$

- Laws of BH Thermodynamics.
- Black Holes Evaporate.
  Where does information go?
- Holographic Principle.
  - t'Hooft, Susskind.
  - Information Paradox.
  - AdS/CFT correspondence.



White Dwarfs

- 1783 -William Herschel.
  - 40 Eridani, triple system, 17 lyr
  - 1910 Henry Norris Russell, Edward Charles Pickering and Williamina Fleming identified it as Spectral Class A.
- 1844 - Friedrich Wilhelm Bessel.
  - Sirius (Canus Major, Dog star, 8.6 lyr) and Procyon (Canus Minor, 12 lyr)
  - Companion white dwarfs.
- 1922 - Coined by Willem Luyten.
  - over 9000, 0.5-0.7$M_\odot$[0.8%-2% $R_\odot$].

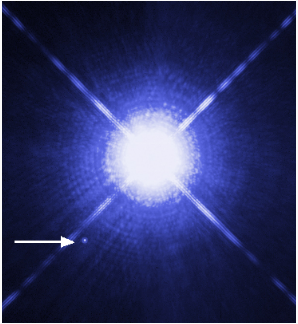


Figure 4: Sirius A and B.

https://en.wikipedia.org/wiki/White_dwarf

White Dwarf Stars Near The Earth

2018 - Astronomers Find Planet Vulcan Right Where Star Trek Predicted it.

Subrahmanyan Chandrasekhar (1910-1995)

- 1930 - At 19, traveled to England.
- Read William A. Fowler's 1926 e^--degeneracy.
    - In fermion gas, electrons move into unfilled energy levels.
    - Particle density increases and electrons fill the lower energy states.
    - Other e^-'s occupy states of higher energy (even at low temperatures).
    - Degenerate gases resist. compression due to the Pauli exclusion principle.
    - Generates a *degeneracy pressure*.
    - Applied Fermi-Dirac statistics.
- Degeneracy pressure vs gravity - **Chandrasekhar limit** - $M \sim 1.44 M_\odot$.

Neutron Stars

- 1932 - Chadwick discovers neutron.
- 1933 - Walter Baade, Fritz Zwicky - neutron stars result of supernovae.
- 1931,1937 - Lev Landau - Work on white dwarfs and neutron stars.
- 1939 - Oppenheimer-Volkoff-Tolman - max $M \sim 0.75 M_{\odot}$[Now, 1.5-3$M_{\odot}$].
- 1965 - Crab Pulsar, 1054 Supernova - Antony Hewish, Samuel Okoye.
- 1967 - Scorpius X-1, Iosif Schlovsky.
- 1967 - Jocelyn Bell, Antony Hewish - PSR B1919+21 first radio pulsar.
- 1974 - Taylor-Hulse binary pulsar.

Figure 5: Crab Nebulae.

Taylor-Hulse Binary Pulsar PSR B1913+16

- Pulsars: pulsating radio star.
  Rapidly rotating neutron star.
- Magnetic lighthouse.
- Regular flashing
  - 2x each cycle - 17 per second.
- Regular variations - 7.75 hrs and 3s differences due to elliptical orbit.
- 305 m Arecibo Radio Telescope in Puerto Rico. (Collapse, Nov. 2020)
- 1993 Nobel Prize
  - Joe Taylor and Russell Hulse.

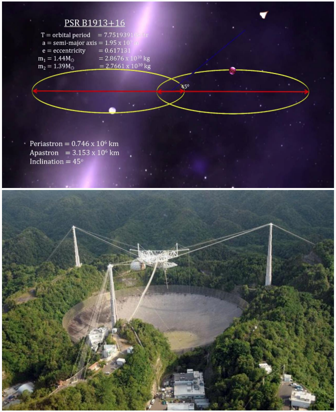


Figure 6: Binary Pulsar and Arecibo Telescope.

Binary Pulsar PSR B1913+16 and General Relativity

- Einstein's Prediction of radiation loss as gravitational waves.
- Calculated masses, periastron (closest distance), and apastron (furthest).
- Energy Loss: $\frac{dE}{dt} = 7.35 \times 10^{24}\text{W}$.
- Orbital period change: $\frac{dT}{dt} = 7.65$ milliseconds/yr.
- First indirect observation of gravitational waves.

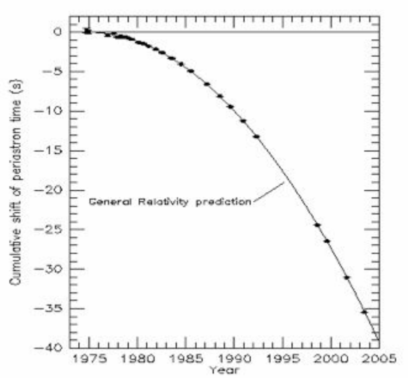
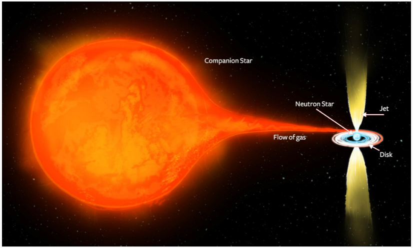


Figure 7: Binary Pulsar Data

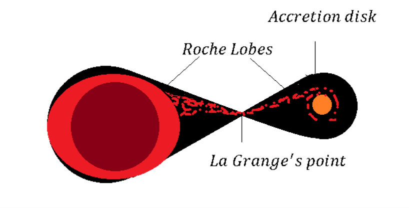
Accretion in Binary Systems

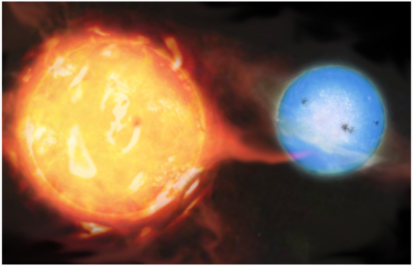
- 1960s - X-Ray Astronomy.
- Scorpius X-1: 1-10 keV.
- 20 sources by end of decade.
- Cygnus X-1 varies in time.
- Accretion.
  - Gas forms disk around compact object.
  - Friction leads to spiraling inward.
  - Gravity and friction compress, raise temperature.
  - Leads to EM emission.



Accretion History

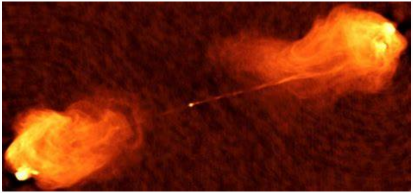
- 1926 Arthur Eddington - accretion rate depends on velocity, density gravity focuses towards CM.
- Hoyle, Lyttleton - rate greater with collisions.
- 1952 Herman Bondi
- Algol in Perseus - eclipsing binary, 2.9 days.
- Small blue hidden by larger red.
- Blue star tending to red giant.
- Used to be red, overflowed Roche lobe - past Lagrange pt.





Active Galaxy Nuclei

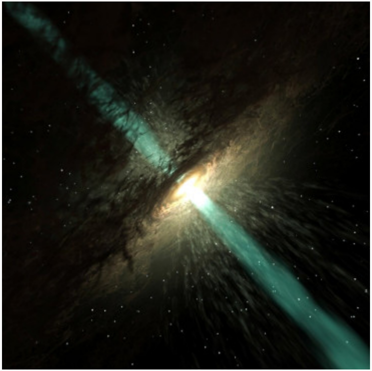
- 1918 - Heber Curtis
  - Straight ray from M87.
- 1920 - Island Universes
  - Curtis-Shapley Debate
- Strange behavior from galaxy centers.
  - Too much blue, UV.
  - Bright.
  - Active galaxies with AGN.
  - Quasars, starbursts.
- Karl Seyfert
  - Intense blue nuclei.
  - Very high velocities.
  - Seyfert galaxies.



- 1954 - W. Baade, R. Minkowski
  - Cynus A
  - 300 $\times$ M31 distance.
  - Dumbbell - lobes.
- 1956-9 - Geoffrey Burbidge
  Lobe energy very high.

Quasars - Quasi Stellar Objects

- 1963 - Hazard, et al. pinpoint 3C 273.
- 1963 - Maartin Schmidt, 3C 273.
  - Spectrum: 16 % redshift
  - Distance: 10^9 lyr.
  - Fluctuating brightness over 1 mo.
- Quasars - QSOs.
- Hubble Telescope detects many.
- AGN Properties:
  - Energy emitted large rate.
  - Extremely compact.
  - Not normal radiation.
  - Gas moves at very high speeds.
- Manifestation of massive BHs.



Massive Black Holes?

- Mass Compactness, M/R, Limits
  - Upper limit on R
    - brightness variation. $R < ct$.
  - Lower limit on M - luminosity.
  - Estimate lifetime energy.
    - luminosity $\times$ age.
    - Eddington limit.
    - 100 million to billions $M_\odot$.
  - $M/R > .001c^2/G$.
- Hoyle, Burbidge - only gravitational collapse can supply energy.

Quasar Models

- 1969 - Donald Lynden-Bell
  - Quasars powered by accretion.
  - BHs > 100 million $M_\odot$.
- Sources of Emission
  - Accretion disk like X-Ray binaries.
  - EM processes
    - Tap spin energy.
    - A flywheel with disk as brake.
- Different emissions
  - X-Rays captured by disk.
  - Turned to UV, optical, IR.
- Need Mass, Spin, and Orientation.

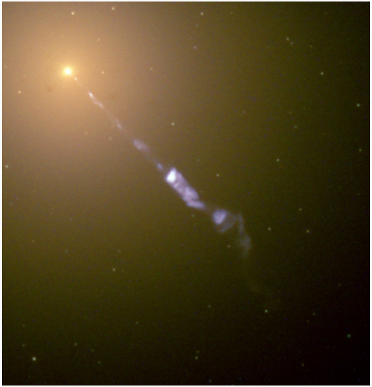


Figure 8: M87 jet.

Radio Astronomy

- 1931 - Karl Jansky
  - Bell Labs - telecommunications.
  - Sensitive antenna
    - transaltantic cable noise.
    - Not terrestrial!.
- 1944 - Grote Reber
  - First sky map of Milky Way.
  - Radio Emissions, Cygnus.
- 1950s - Martin Ryle
  - Idea of arrays of dishes.
- 1970s - Telescope arrays.
- Detailed hot spots and lobes.

VLA - Very Large Array
- Socorro, NM.
27 linked radio telescopes.
25 m diameter.
Y-shaped across 40 km.
Comparable to Hubble resolution.

Hot Spots and Lobes

- Picked up double radio sources.
- From galaxy cores.
- Superhot, magnetized gas ejection?
- 70s - Blobs powered by twin streams of gas from galactic core hotspot.
  - Source of radio waves.
- Travels through intergalactic medium, pushing matter away at 60% c.
- Deceleration leads to shock waves.
- Energy of relativistic e^-'s and magnetism. - Synchrotron radiation.
- Hot spot - 100,000 to 10^6 yrs.
- Moves to lobes, persists 10^8 yrs.

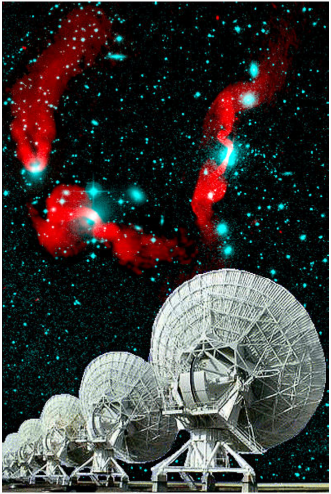
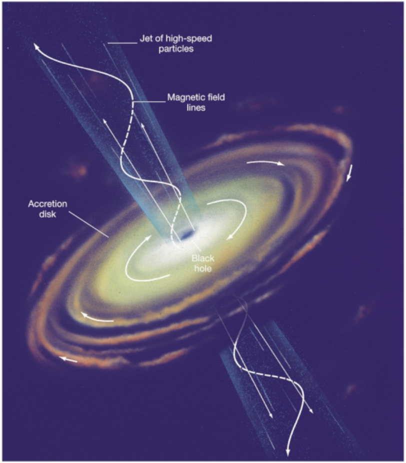


Figure 9: Radio Galaxies and Quasars

Jets

- 1978 - Jets only theoretical.
- Not seen to this point.
- VLA observations changed that.
- Late 1978 - SS 443 X-ray binary.
- Bruce Margon, et al.
  - Spectrum had three parts:
  Normal, red shifted, blue shifted.
- Rotating jets precessing - 163 days.
- Stability due to high speed, low density, stiff B-field.
- Can lead to radio trail bend.
- Then there is the core using VLBI.



Black Holes - The Last Decade

- 2014- *Interstellar,* the movie.
  - Black hole visualization.
- 2016 - Gravitational Waves, LIGO.
- 2019 - First picture, Event Horizon.
- Nobel Prizes:
  - 2011 - Saul Perlmutter, Brian P. Schmidt and Adam G. Riess.
  - 2017 - Rainer Weiss, Barry C. Barish and Kip S. Thorne.
  - 2019 - James Peebles, Michel Mayor and Didier Queloz.
  - 2020 - Roger Penrose, Reinhard Genzel and Andrea Ghez
- Now, back to physics ...