White Dwarfs

Observational Properties

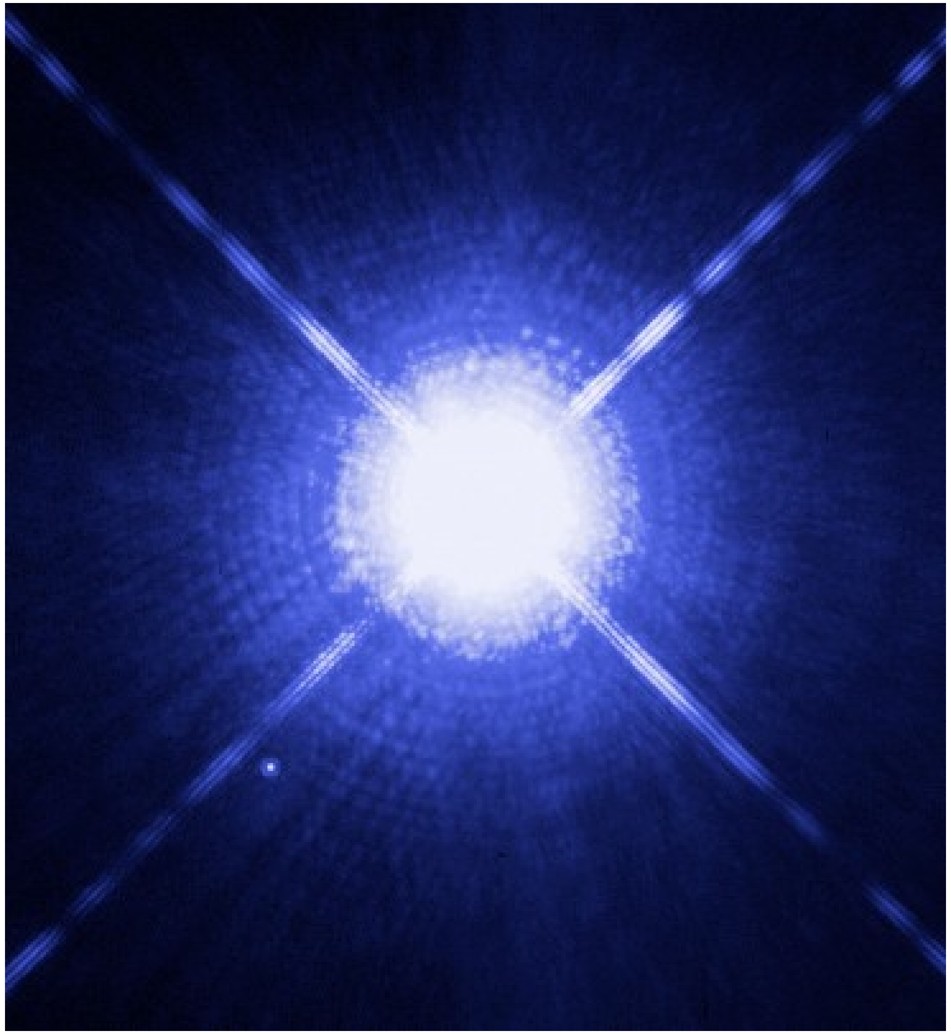
The Helix Nebula is one of brightest and closest examples of a planetary nebula, a gas cloud created at the end of the life of a Sun-like star. The outer gasses of the star expelled into space appear from our vantage point as if we are looking down a helix. The remnant central stellar core, destined to become a white dwarf star, glows in light so energetic it causes the previously expelled gas to fluoresce. The Helix Nebula, given a technical designation of NGC 7293, lies about 700 light-years away towards the constellation of Aquarius and spans about 2.5 light-years. The above picture was taken by the Wide Field Imager on the 2.2-meter Telescope at the European Southern Observatory's La Silla Observatory. A close-up of the inner edge of the Helix Nebula shows complex gas knots of unknown origin.

http://apod.nasa.gov/apod/ap090303.html

Credit: WFI, MPG/ESO 2.2-m Telescope, La Silla Obs., ESO

History

- Different sources give different histories (it seems). Here's Wikipedia's history…
- Many sources (incl. Wikipedia) says 40 Eridani (a triple system) had the first WD discovered
  - Pair (B/C) discovered by Herschel (1783)
  - Recognized in 1910 that 40 Eridani B was white in color (implies hot surface)
    - Hard to understand given its low mass
- Sirius B next discovered
  - First observed in 1862 (unseen companion already known from astrometry)
  - Spectrum observed in 1915—again characteristic of a hot A star
- First isolated WD discovered in 1917



NASA, ESA, H. Bond (STScI), and M. Barstow (University of Leicester)

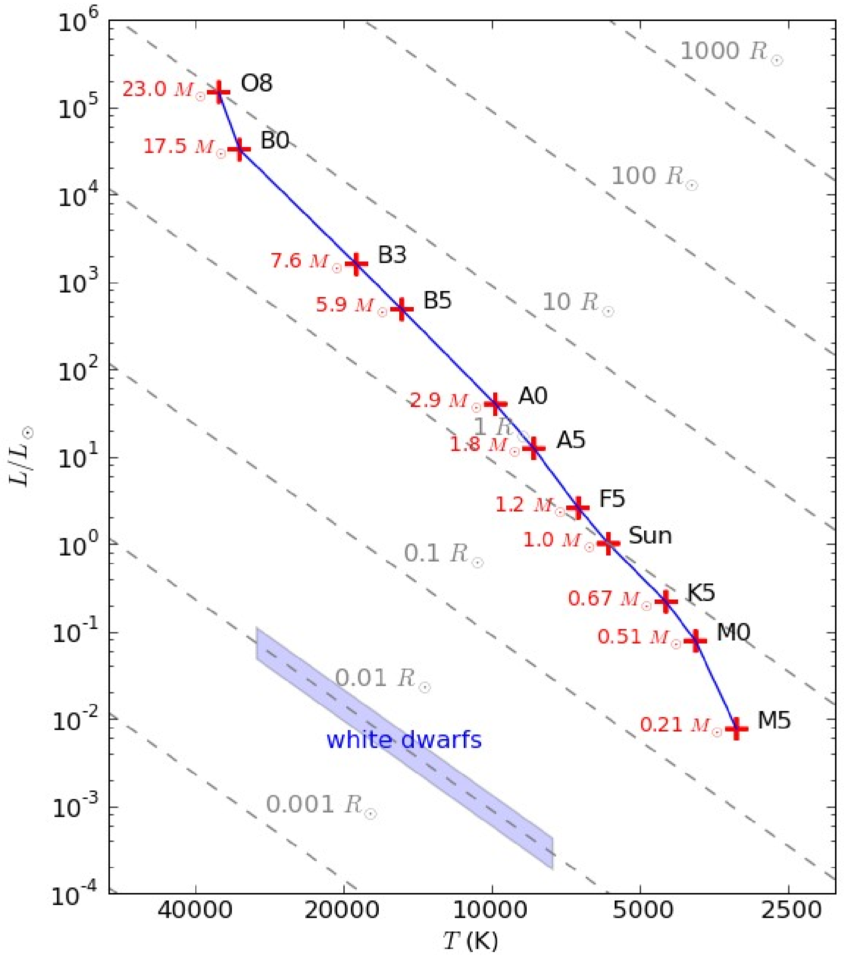
http://www.spacetelescope.org/images/heic0516a/

Observational Properties

- White dwarfs appear as a distinct group in the H-R diagram
- We don't find any with luminosities below

$$L \sim 3 \times 10^{-5} L_\odot$$

- We expect WDs to start out hot and cool as they age
- Since they are supported by degeneracy, the radius doesn't change much as they cool



Observational Properties

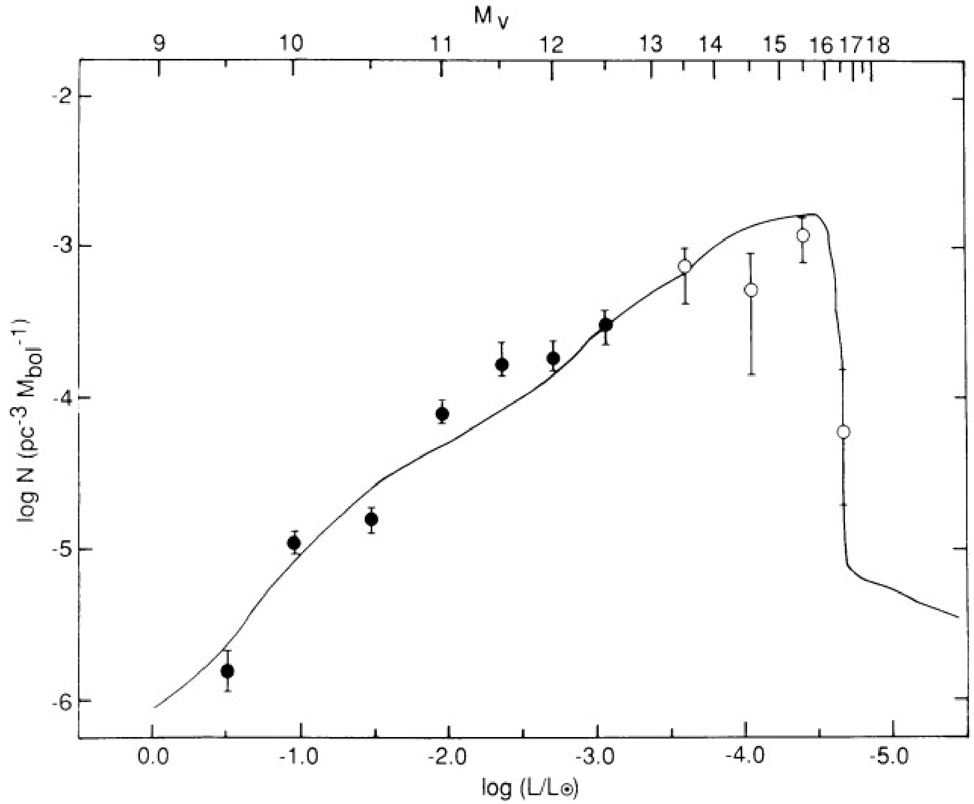


FIG. 1.—The white dwarf luminosity distribution. The circles represent the observed number of white dwarfs in each luminosity bin; the solid line shows the theoretical distribution. The vertical axis, Φ, is log N ($\mathrm{pc}^{-3} M_{\mathrm{bol}}^{-1}$).

(Winget et al. 1987)

Observational Properties

- Tight group
- Radius is ~ 0.01 solar radii
  - From luminosity and B-V
- Spectra give surface gravities
  - Single WD masses are ~ 0.6 ± 0.1 solar masses
- WDs in binary systems have wider range of masses

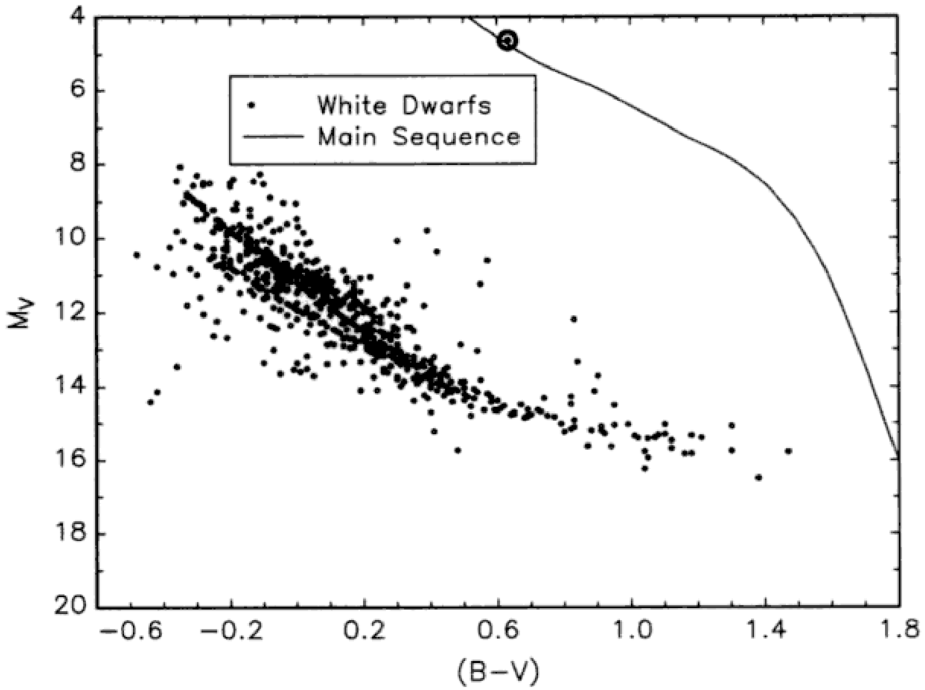


Fig. 2.15. A color–magnitude HR diagram for white dwarfs from data given by McCook and Sion (1999). A ZAMS with the sun is shown to help orient you. An effective temperature of 10,000 K is at B–$V \approx 0$.

(Hansen, Kawaler, Trimble)

Observational Properties

Spectral type	characteristics
DA	Balmer lines only
DB	He I lines; no H or metals
DC	Continuous spectrum, no lines
DO	He II strong; He I or H present
DZ	Metal lines only; no H or He lines
DQ	Carbon features
P (suffix)	Magnetic WD w/ detectable polarization
H (suffix)	Magentic WD w/o polarization
X (suffix)	Peculiar/unclassifiable
E (suffix)	Emission lines
? (suffix)	uncertain
V (suffix)	variable

(from HKT)

- Spectra vary widely—surface composition may evolve
- DA are most common (80%); DB next most common (~20%)

Observational Properties

- Effective temperatures range from 100,000 K to < 4000 K
  - Most are hotter than the Sun → "white"
  - Cool with time
- WDs rotate
  - P usually longer than few hours
  - Longer than the rate that angular momentum conservation would yield for the Sun

Aside: Critical Rotation

- How fast could a WD spin?
  - Conserve angular momentum as Sun contracts to WD size

$$\omega_\odot R_\odot^2 = \omega_{\rm WD} R_{\rm WD}^2$$

$$\left(\frac{\omega_{\rm WD}}{\omega_\odot}\right) = \left(\frac{R_\odot}{R_{\rm WD}}\right)^2 = (100)^2 = 10^4$$

  - Sun's period is ~30 days, so WD period could be 0.07 hours (4 minutes)

- What is the limit though?
  - Breakup rate:

$$\frac{GMm}{R^2} > \frac{mv^2}{R} \rightarrow \frac{4\pi^2 R^3}{G} < MP^2$$

  - For a 1 solar mass, ~8000 km WD, P ~ 12 s for breakup

Evolution

- Generally, we can have different composition WDs
  - For low mass stellar evolution, He burning never happens, and He Wds are made—these will be very low mass
  - Otherwise, we generally expect C/O WDs
  - The highest mass stars (that don't supernovae) may make O/Ne/Mg WDs

- We know that the interior will be degenerate
- Surface will be non-degenerate
  - T is very high at birth
  - Different EOS and opacity at surface
- Cooling problem will have to consider these distinct regions
  - Surface controls the cooling rate

Cooling

- We'll work out a simple model of white dwarf cooling
- Core:
  - Degenerate
  - Contains nearly all the WD mass
  - Extends for nearly the entire WD radius
- We need to assume that there is no
  - Nuclear energy generation
  - Gravitational contraction
  - Neutrino losses
- Finally, we'll assume that the envelope is completely radiative
- Abrupt transition from degenerate to non-degenerate at $r = r_{\rm tr}$
  - Recall from Ch. 3, comparing the Fermi momentum to kT, we found

$$\rho_{\rm tr} \sim 6 \times 10^{-9} \mu_e T_{\rm tr}^{3/2}$$

  - Conduction highly efficient in the core, so we take $T_{\rm core} = T_{\rm tr}$
- Envelope:
  - Thin
  - Ideal gas holds

Cooling Curves

- The drop off in the number of low luminosity WDs tells us about the ages of the different components of the galaxy

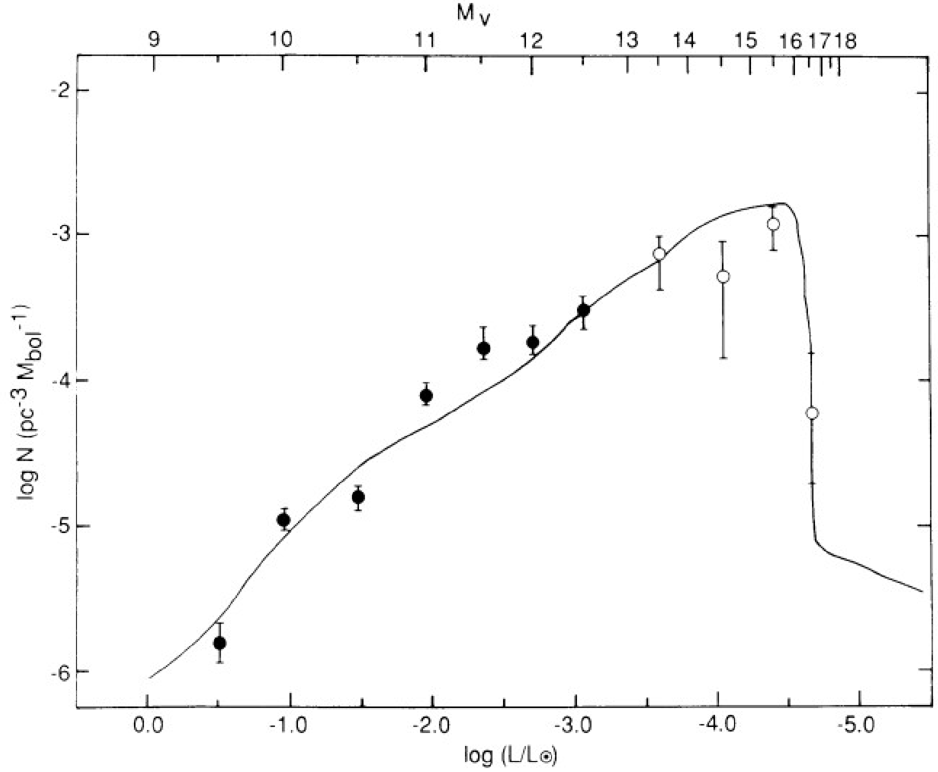


FIG. 1.—The white dwarf luminosity distribution. The circles represent the observed number of white dwarfs in each luminosity bin; the solid line shows the theoretical distribution. The vertical axis, Φ, is log N (pc$^{-3}M_{\rm bol}^{-1}$).

$$t_{\rm cool} = 6 \times 10^6 \ {\rm yr} \left(\frac{A}{12}\right)^{-1} \left(\frac{M}{M_\odot}\right)^{5/7} \left(\frac{\mu}{2}\right)^{-2/7} \left[\left(\frac{L_\star}{L_\odot}\right)^{-5/7} - \left(\frac{L_0}{L_\odot}\right)^{-5/7}\right]$$

More Realistic Cooling

- We've neglected a lot of physics
- Initial conditions
  - What happens during the planetary nebula phase?
  - Usually take a hot WD resulting from some 1-d stellar evolution
    - Requires some prescription for mass loss
- Composition
  - C/O is a good assumption
  - More massive WDs may have O/Ne/Mg
  - Outer layers are likely H/He + heavies
    - Depends on mass loss history + how far nucleosynthesis reached
    - Observational determination of surface composition is hard (hot T means lines in UV)
    - Two popular models: pure He (DB) or H above He (DA)
      - Thickness constrained because otherwise burning would take place

More Realistic Cooling

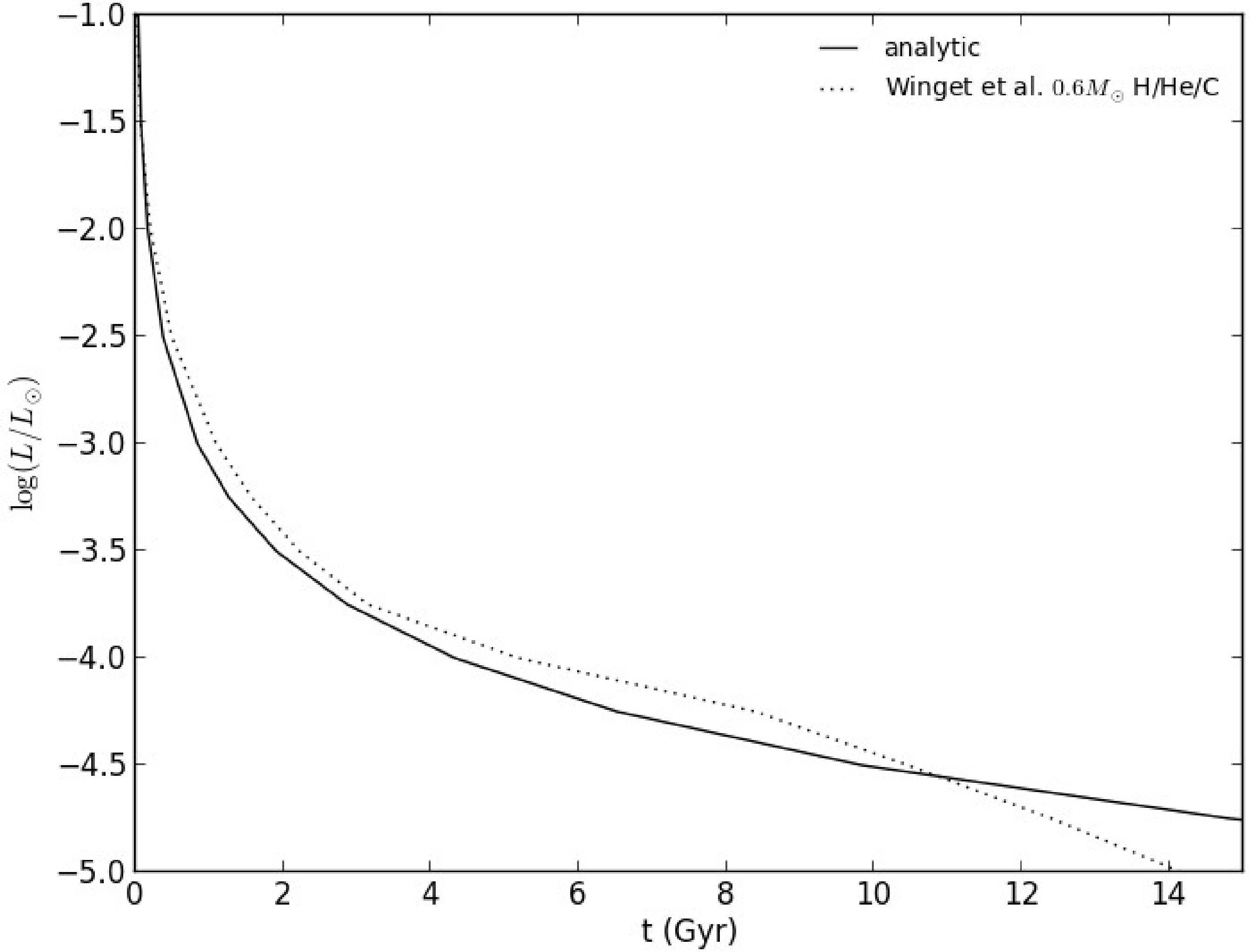
- Crystallization
  - Recall for a WD, as the temperature cools, for the ions, the Coulomb potential can dominate over kT

$$\Gamma_C \equiv \frac{Z^2 e^2}{akT}$$

  - At large Γ (~170), the ions settle into a lattice
  - Latent heat of crystallization slows the cooling
  - C and O separately can crystallize at different times
    - O goes first, differentiates and gravitational PE is released that also slows cooling
- Convection
  - We are heating from below—convection can occur
  - Alters the heat transport and therefore the cooling timescale
  - Convection also mixes the surface composition—changing spectral type

More Realistic Cooling

- Cooling curve from Winget et al. (1987)



Magnetic WDs

- Some WDs have strong (106 G) magnetic fields
  - Sun is 1 G
- This may be a remnant of the formation (flux freezing)
- We'll use the Sun as an example
- First question: Can the Sun's magnetic field survive the late stages of stellar evolution?
  - Dynamo action is likely over now (no longer convective)

Magnetic Fields

- Recall the MHD induction equation

$$\frac{\partial B}{\partial t} = \nabla \times (v \times B) + \frac{c^2}{4\pi\sigma}\nabla^2 B$$

  - What happens in the absence of generation—just consider last term
  - Left with a diffusion equation

- Diffusion timescale (dimensional analysis)

$$t \sim \frac{4\pi\sigma L^2}{c^2}$$

  - Here L is a characteristic lengthscale over which the field changes

Magnetic Fields

- Magnetic conductivity
  - HKT gives an estimate for this (Spitzer 1962)

$$\sigma \sim 1.4 \times 10^8 \frac{T^{3/2}}{\ln \Lambda} \qquad \Lambda = 10^4 \frac{T^{3/2}}{n_e^{1/2}}$$

  - Evaluating, we get a decay time of 2×10^{11} yr
  - Field should survive through evolution (although planetary nebula phase can be tricky…)

- For the field strength of the WD, we use flux freezing (since conductivity is large)

$$B_\odot R_\odot^2 = B_{\rm WD} R_{\rm WD}^2$$

  - 1 G field will become 10^4 G

Magnetic Fields

- How long can a WD retain its field?
  - Once again, this is decay
  - Magnetic conductivity is now for degenerate matter (Wendell et al. 1987):

$$\sigma = 10^9 \frac{T^2}{\rho \kappa_{\rm cond}} \approx 2 \times 10^{15} \rho \ {\rm s}^{-1}$$

  - This gives a lifetime of (again) 2 × 10^{11} yr

- Finally, really strong magnetic fields can alter the cooling…