H-R Diagrams & Stellar Evolution:

Modeling the Stars: How Do We Determine the Structure and Evolution of Stars?

The "physics" of stars: the equations & numerical models of stellar structure represent the known physics needed to determine the interior structure of a star and to predict its overall surface properties over time (stellar evolution). The balance between gravity (pulling the star's mass together) and pressure (pushing it apart) can be thought of as the main physical effect that determines the final structure and surface properties of a star. This effect is described primarily by the equation for hydrostatic equilibrium. However, the equation of hydrostatic equilibrium is only one of four interconnected equations that are used for modeling the interior and surface properties of stars.

Hydrostatic equilibrium:

$$dP/dr = -GM(r)\rho(r)/r^2$$

$$P(r) = k\rho(r)T(r)/\mu(r)m_H \text{ (Equation of State)}$$

Mass continuity:

$$dM/dr = 4\pi r^2 \rho(r)$$

Energy transport (radiative and convective):

$$dT/dr = \left[-3\kappa(r)\rho(r)/64\pi\sigma r^2 T^3(r)\right]L(r)$$

$$dT/dr = (1 - 1/\gamma)\left[T(r)/P(r)\right]dP/dr$$

Energy generation (thermal equilibrium):

$$dL/dr = 4\pi r^2 \rho(r)\varepsilon(r)$$

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a. Hydrostatic equilibrium: describes the "contest" between gravity and pressure which ultimately determines the star's structure

b. Conservation/continuity of mass: describes the mass as a function of radius and relates the mass and its associated gravity forces

c. Energy transport (either via radiation, or convection - convection needing a semi-empirical treatment): describes how energy is transported throughout the structure of the star

d. Energy generation through nucleosynthesis or gravitational contraction: describes the fusion reactions that provide the energy generation which maintains pressure against gravity or the conversion of gravitational energy into heat energy that occurs mostly during the pre-MS stages of a star's life

H-R Diagrams & Stellar Evolution:

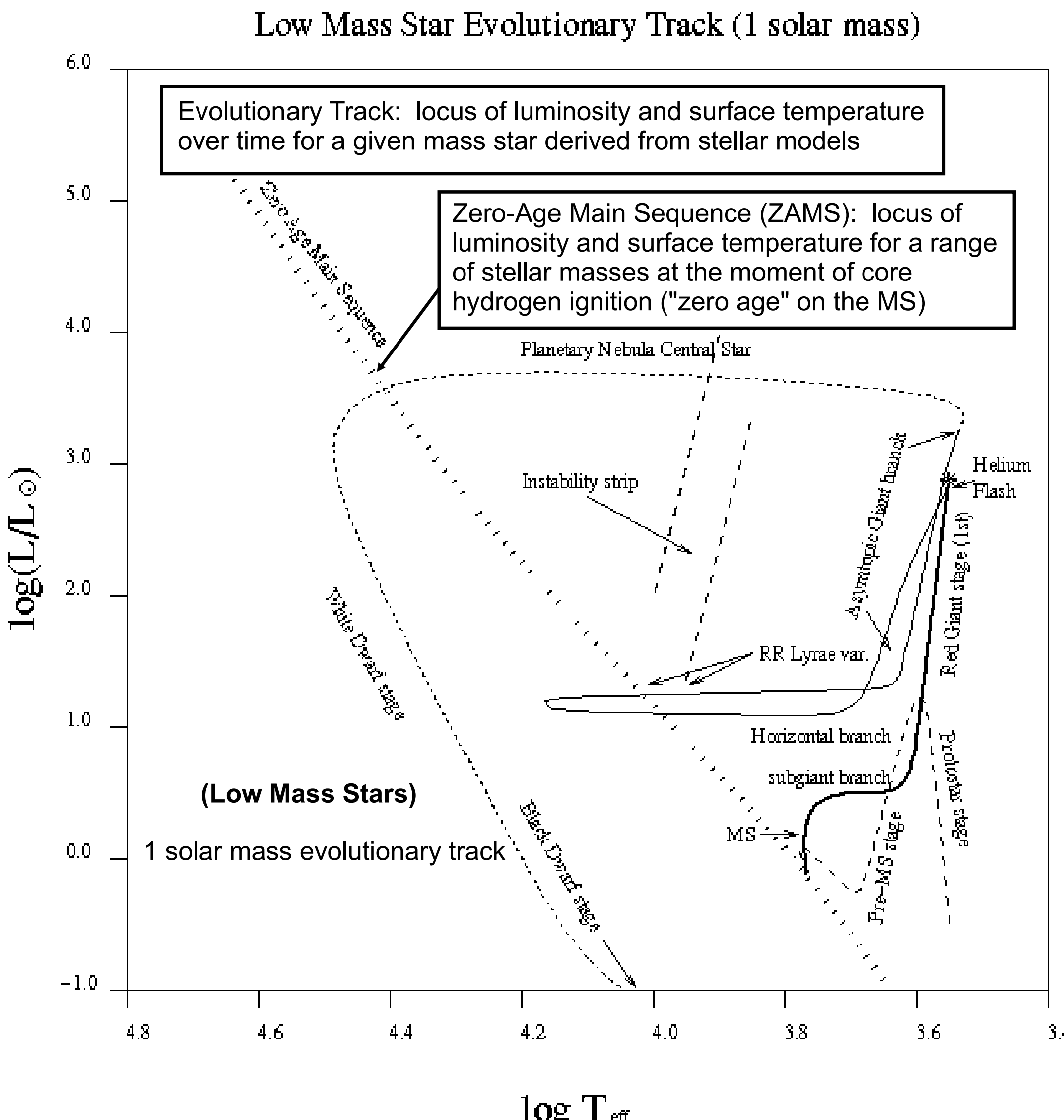
The only way to solve the linked system of equations that describes the physics of stars is by computer modeling.

Computer modeling can determine the interior structure and surface properties of stars by solving (integrating) the above equations simultaneously. It also describes the changes in a star's interior structure and surface properties over time (stellar evolution). Early models were "one dimensional"; all equations were written only as a function of radius. More realistic models using 2-D or 3-D modeling techniques can more fully take into account the energy transport via convection rather than using the semi-empirical approximation of 1-D models.

Link to a shockwave app that lets you graphically evolve different mass stars: Watch stars evolve across the HR diagram.

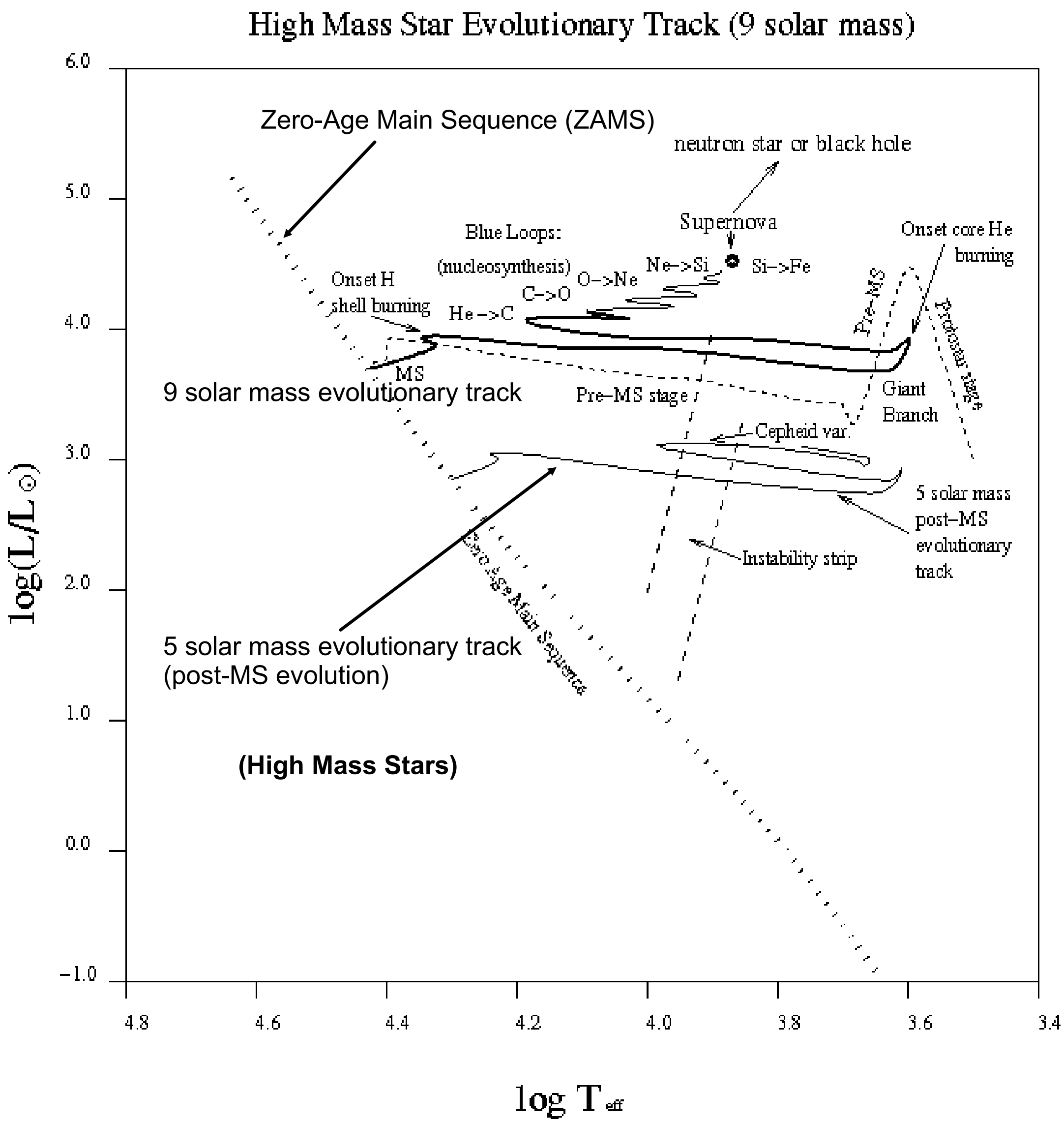
~~Link to an on-line version of the computer models referred to above, submit mass, composition & 2 parameters concerning convection to compute the interior structure of a ZAMS star: Michael Briley's "The Stellar Interior Construction Site"~~ (unfortunately, this site seems to be permanently disabled)

Evolutionary tracks: the results of stellar modeling



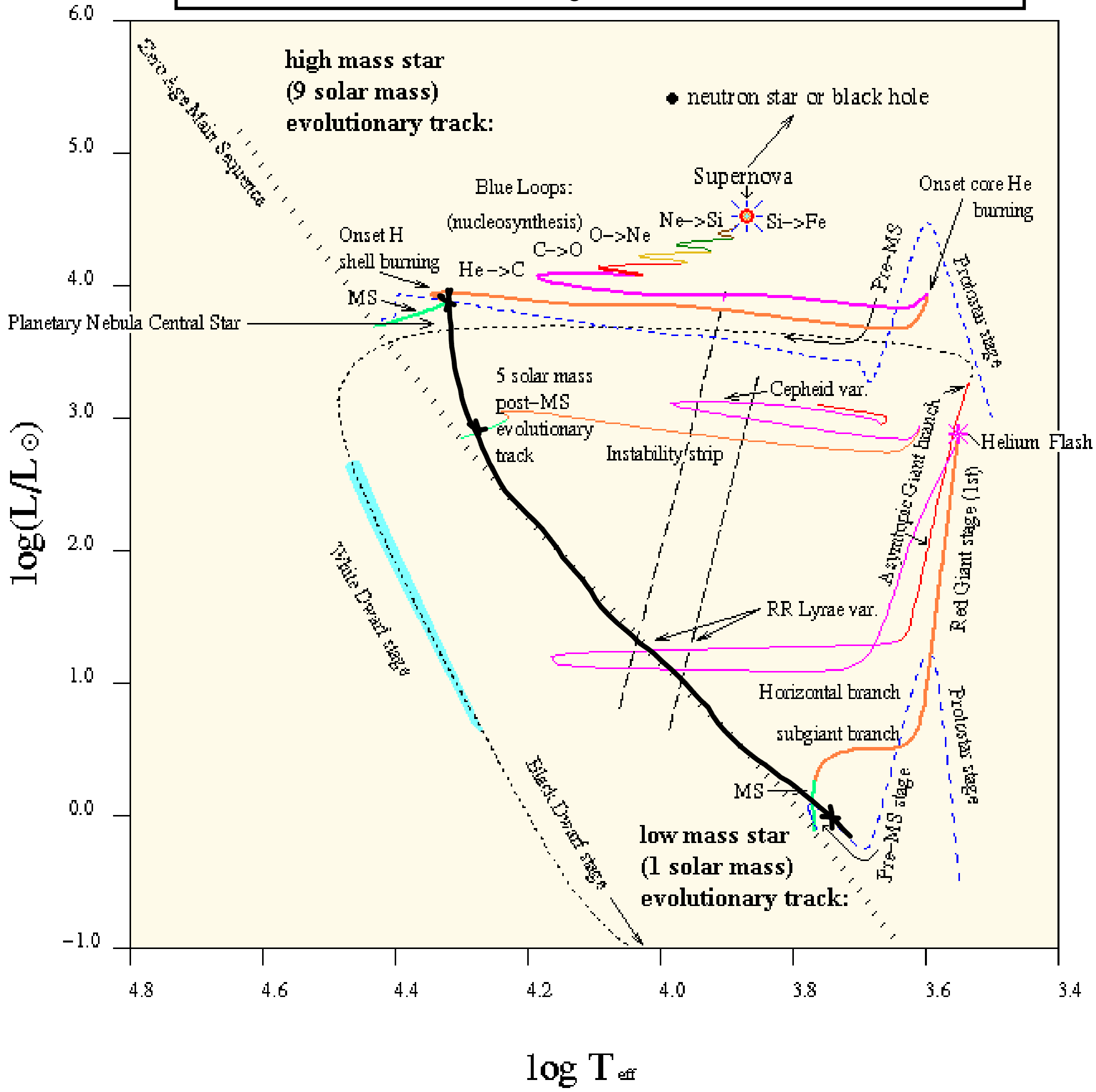
Stellar model input:
Mass, Composition, Empirical Convection Data (1-D)

Stellar model output:
Luminosity, Surface Temperature, Interior Structure - by reiterating the model over time steps an evolutionary track may be output


High Mass Star Evolutionary Track (9 solar mass)
Zero-Age Main Sequence (ZAMS)
neutron star or black hole
Supernova
Blue Loops:
(nucleosynthesis)
Onset core He burning
Ne->Si
Si->Fe
O->Ne
C->O
He->C
Onset H shell burning
Pre-MS
Protostar stage
MS
9 solar mass evolutionary track
Pre-MS stage
Giant Branch
Cepheid var.
5 solar mass post-MS evolutionary track
Instability strip
Zero-Age Main Sequence
5 solar mass evolutionary track
(post-MS evolution)
(High Mass Stars)
log(L/L☉)
log T eff
6.0
5.0
4.0
3.0
2.0
1.0
0.0
-1.0
4.8
4.6
4.4
4.2
4.0
3.8
3.6
3.4

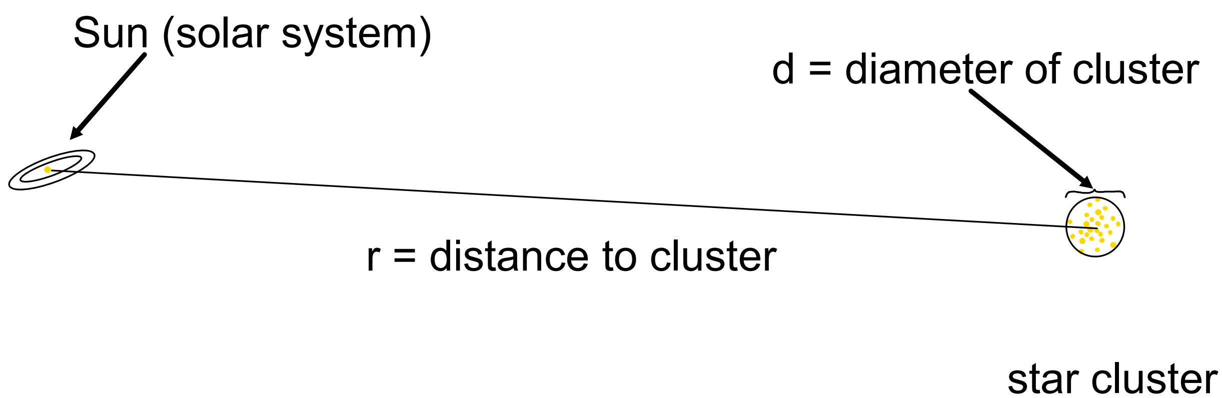
World's "busiest" H-R diagram!!!

Isochrone: locus of luminosity and surface temperature for a range of stellar masses, all at the same age or time from formation

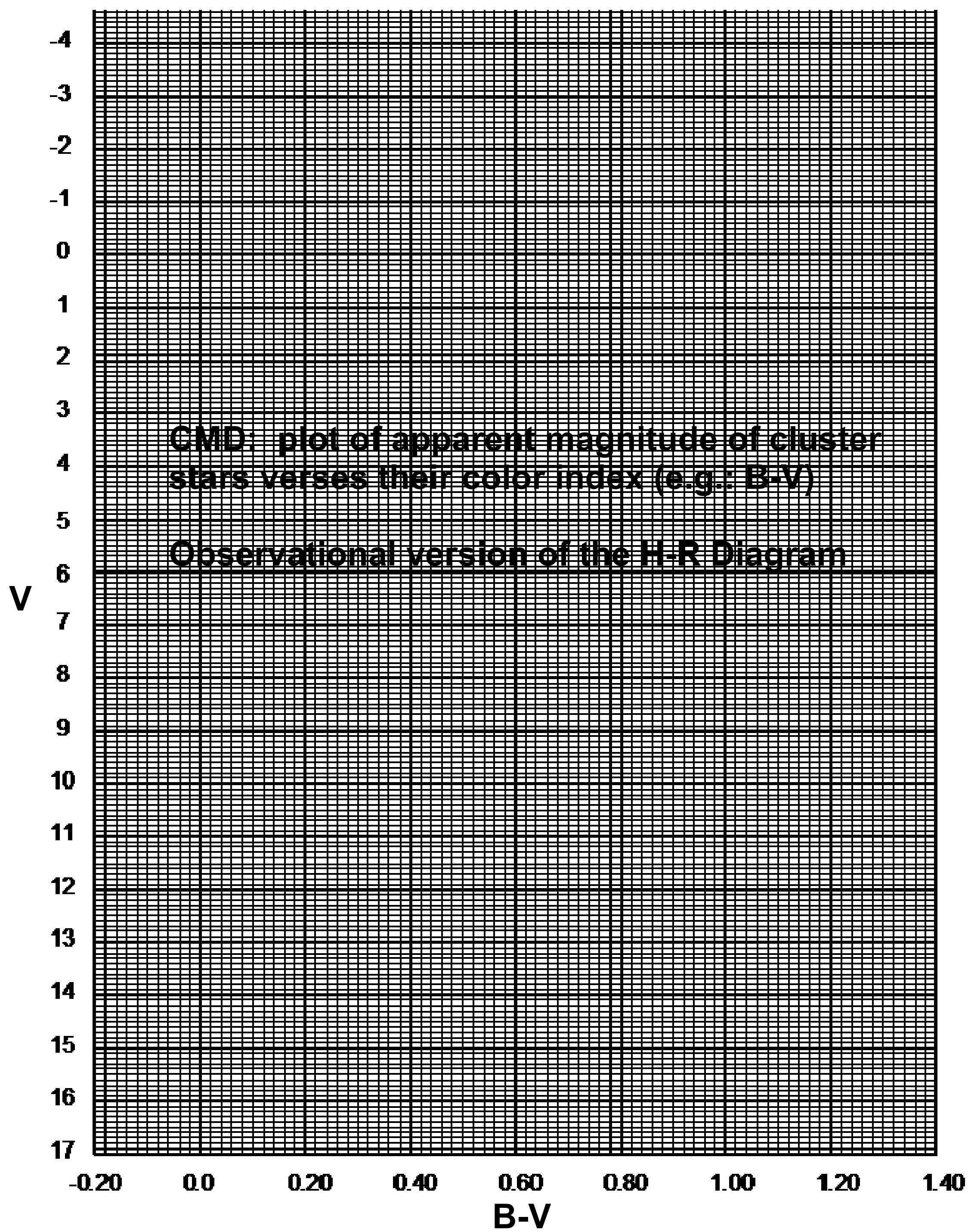


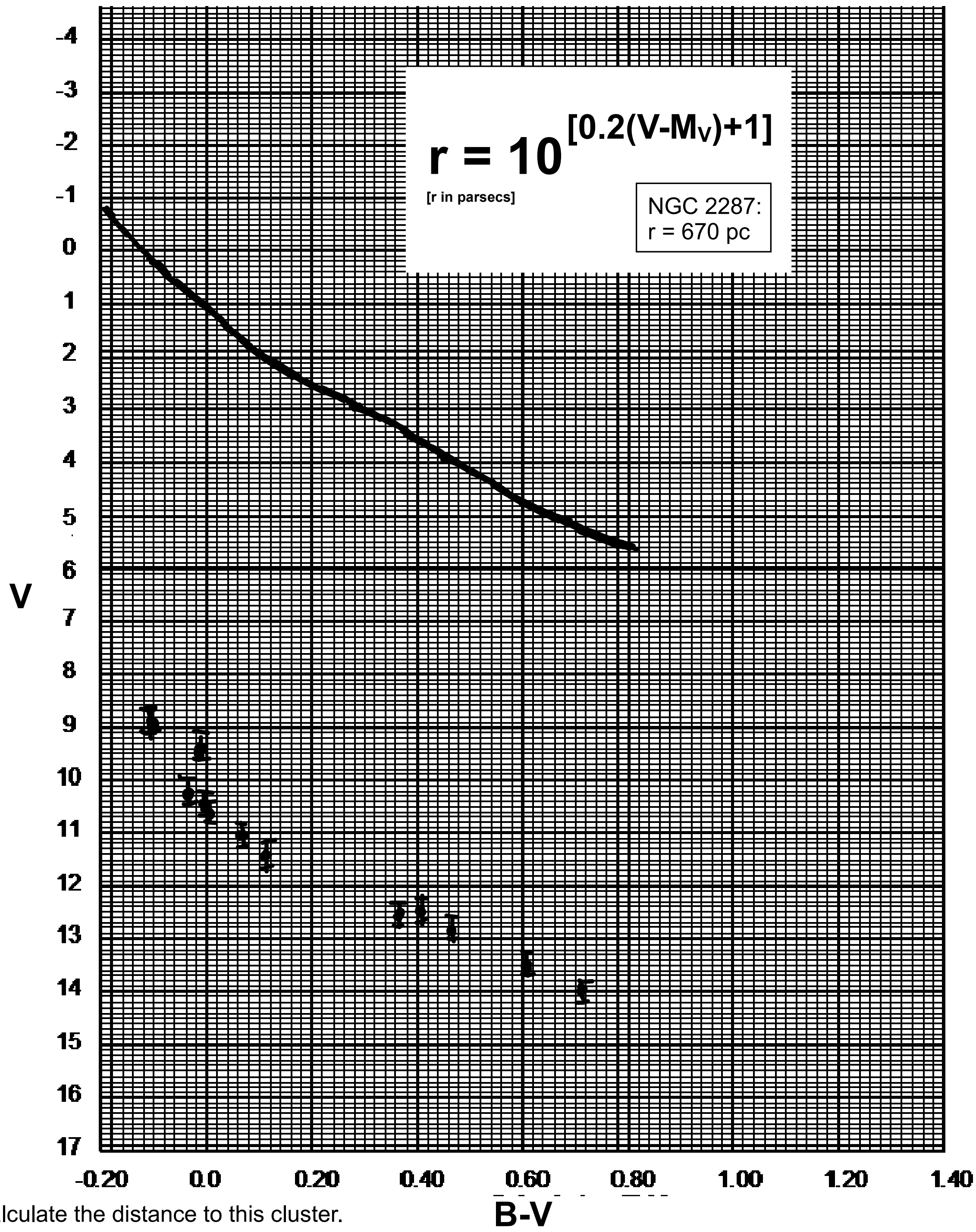
Draw an isochrone on this H-R Diagram using the post-MS evolutionary tracks for the 1, 5, and 9 solar mass stars.

Using Color-Magnitude Diagrams (CMD) of clusters as probes of stellar evolution and MS fitting method (standard candle distance measuring technique:



1. r >> d, stars in cluster are all equal distance from the Sun
2. Stars in cluster are all the same age (began forming at the same time)
3. Stars in cluster are all the same composition (formed out of the same gas cloud)
4. Stars in cluster vary in mass


CMD: plot of apparent magnitude of cluster stars verses their color index (e.g.: B-V)
Observational version of the H-R Diagram
V
-4
-3
-2
-1
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
-0.20
0.0
0.20
0.40
0.60
0.80
1.00
1.20
1.40
B-V



Calculate the distance to this cluster.