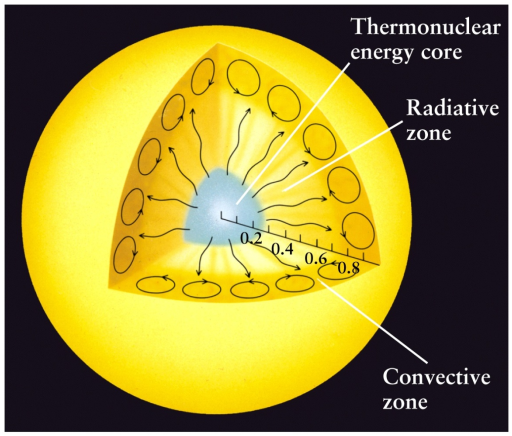
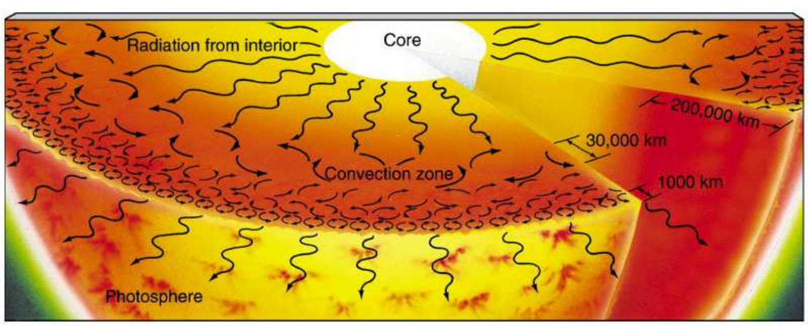
# Interior of the Sun



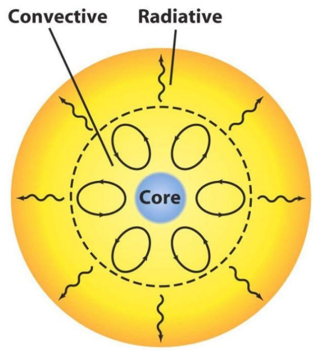

*Universe* by Freedman, Geller, and Kaufmann

# Energy Transport




*Astronomy Today*, Chaisson and McMillan

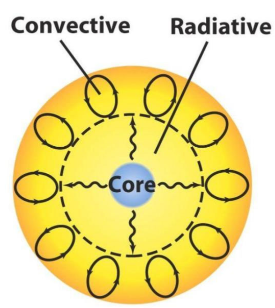
# Interior of a High-Mass Star




**(a) Mass more than about 4 $M_{\odot}$: Energy flows by convection in the inner regions and by radiation in the outer regions.**

*Universe* by Freedman, Geller, and Kaufmann

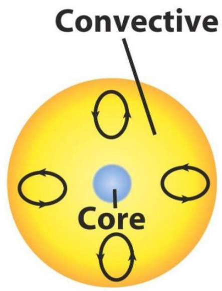
# Interior of a Solar-Like Star




**(b) Mass between about 4 $M_{\odot}$ and 0.8 $M_{\odot}$: Energy flows by radiation in the inner regions and by convection in the outer regions.**

*Universe* by Freedman, Geller, and Kaufmann

# Interior of a Low-Mass Star



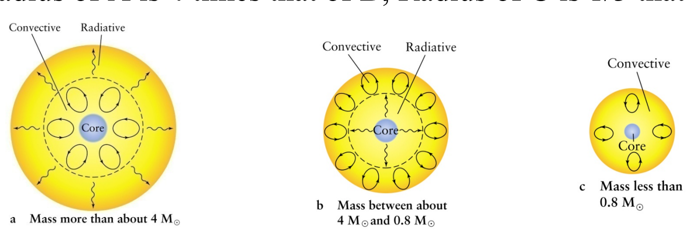

**(c) Mass less than 0.8 $M_\odot$: Energy flows by convection throughout the star's interior.**

*Universe* by Freedman, Geller, and Kaufmann

# Interior Structure

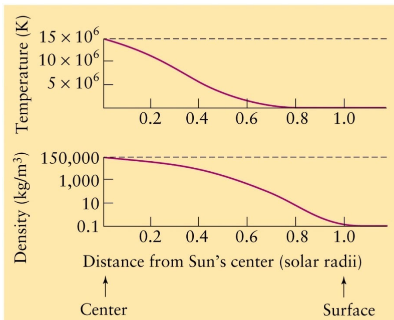
A) Core is convective and outer layers are radiative.
B) Core is radiative and outer layers are convective.
C) Entire star is convective.

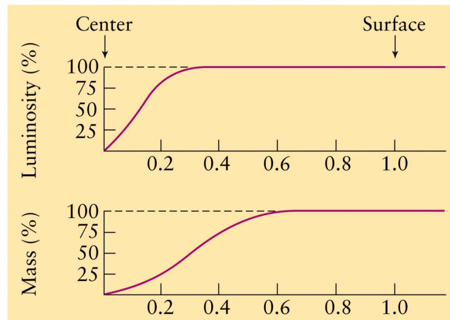
Radius of A is 4 times that of B; Radius of C is 1/3 that of B.




*Universe* by Freedman, Geller, and Kaufmann

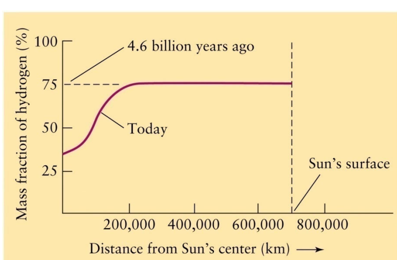
# Internal Characteristics

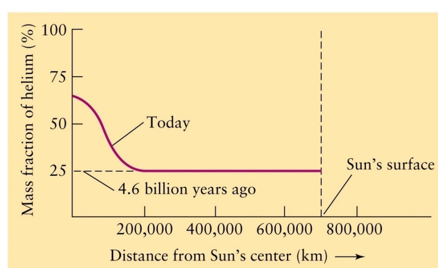



*Universe* by Freedman, Geller, and Kaufmann

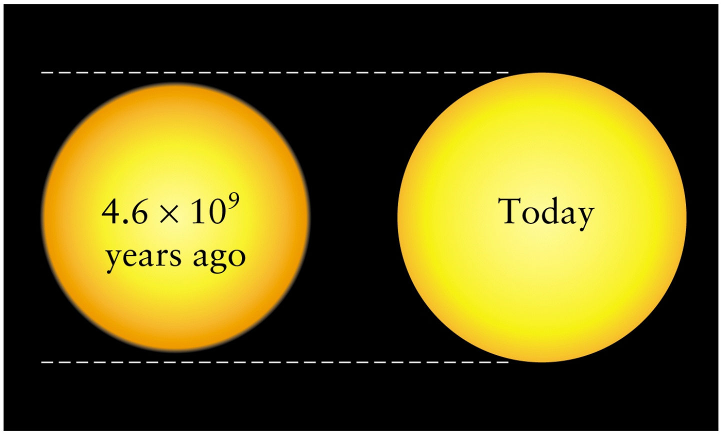
# Abundance Changes




*Universe* by Freedman, Geller, and Kaufmann

# Size Change




*Universe* by Freedman, Geller, and Kaufmann

# Question

If stars exist for billions of years but mortals live less than a century,

How are we able to study, derive, and understand Stellar Evolution?

## Astronomical Insight

Iterative Process Involving

- Acquisition of Data
- Development of Models
- Refinement of Theories

## Astronomical Tools

Determine the Brightness of Stars

- Magnitudes
- Colors

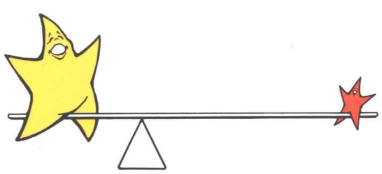
# Astronomical Tools

Analyze the Spectra of Stars

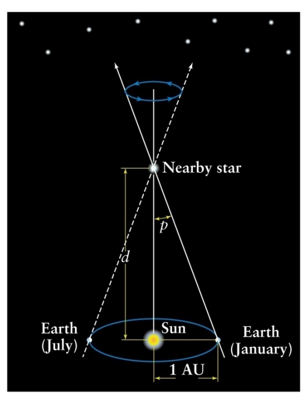
- Chemical Composition
- Surface Temperatures
- Radii

# Astronomical Tools

Get Masses from Binaries



Get Distances from Parallaxes




*Universe* by Freedman, Geller, and Kaufmann

# Statistical Results

Photometry

Spectroscopy

Masses

Distances

# Relationships

$E \propto \mathcal{M}$

$L \propto \mathcal{M}^4$

Lifetime = ( Total Energy ) / ( Rate Energy is Used )

$\tau \propto E / L$

So $\tau \propto E / L = \mathcal{M} / \mathcal{M}^4$

$\tau \propto 1 / \mathcal{M}^3$

# Example

$\tau \propto 1 / \mathcal{M}^3$

Main Sequence lifetime of the Sun = $10 \times 10^9$ years

Let $\mathcal{M}$ = 2 solar masses

$\tau = (10 \times 10^9 \text{ yr}) / \mathcal{M}^3$

Then $\tau = (1 / 2^3)\, 10 \times 10^9 = 1.25 \times 10^9$ years

# The HR Diagram

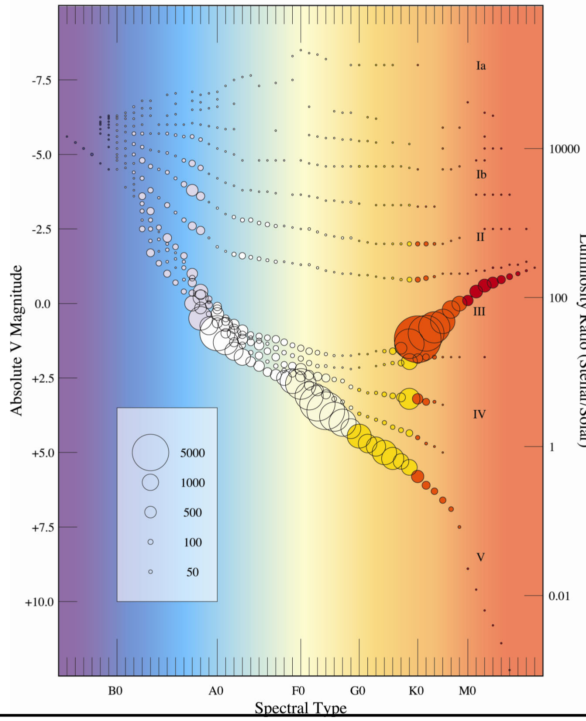
Intrinsic Brightness

Surface Temperature

Radii

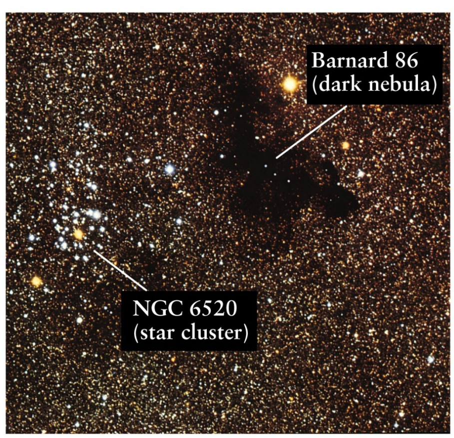
Mass (on the Main Sequence)

**(Let's filter by) Age**




# Star Clusters

## Observational Testbeds of Stellar Evolution




Australian Astronomical Observatory / David Malin Images

## Evolution

Stars have a Birth, Life, and Death

Star Clusters have a Birth, Life, and Death

## Advantages of Star Clusters

1. All members have the Same Distance from the Sun

2. All members have the Same Age

3. All members have the Same Chemical Composition

## Types of Star Clusters

### Open Clusters

1100+ Clusters

Spiral Arms

50 to 1000 Stars

10 pc Diameter

## Types of Star Clusters

### Globular Clusters

~150 Clusters

Halo

10,000+ Stars

100 pc Diameter

## How Do We Determine Age?

We have HR Diagram "snapshots" of many clusters.

These clusters were not "born" at the same time.

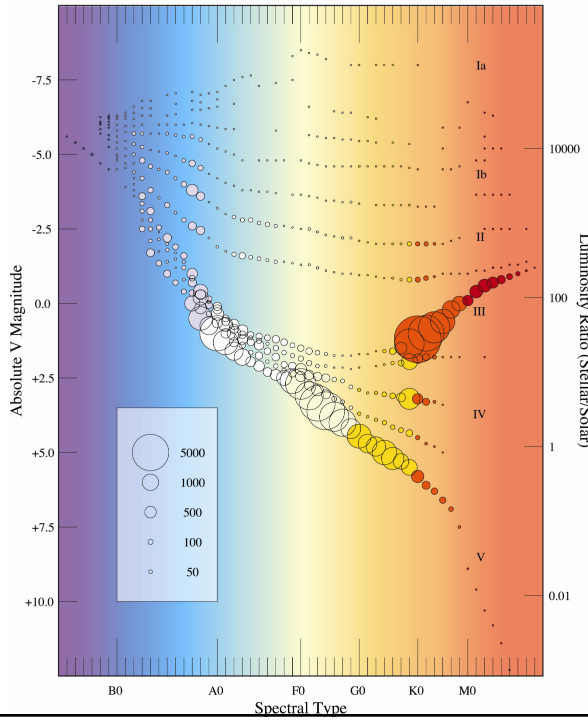
Stellar Evolution is a function of Mass, so let's compare HR Diagrams to get an understanding of the cluster's Age.

## Features to Note on CM Diagrams

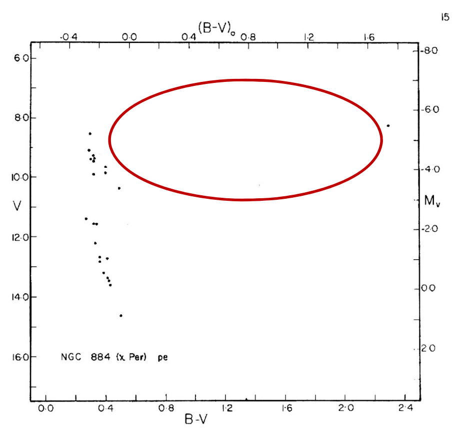
The Top of the Main Sequence

The Shape of the Main Sequence

The Other Populated Areas

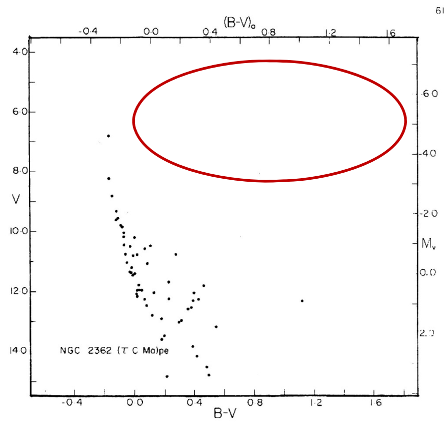



# χ Per



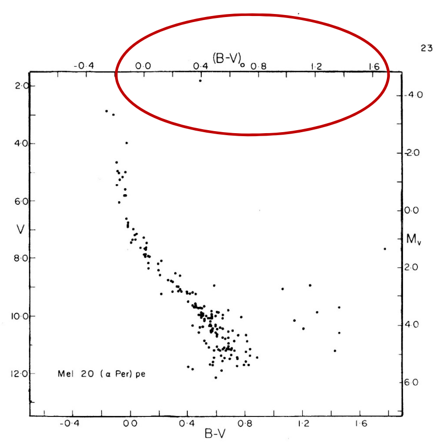

*Atlas of Open Cluster CM Diagrams*, Hagen

# NGC 2362



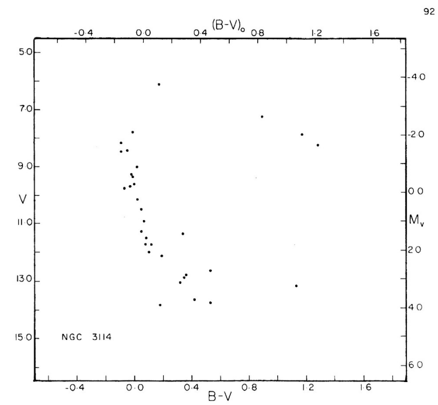

*Atlas of Open Cluster CM Diagrams*, Hagen

# Mel 20



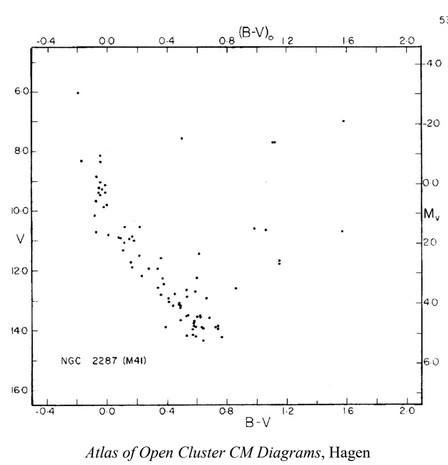

*Atlas of Open Cluster CM Diagrams*, Hagen

# NGC 3114



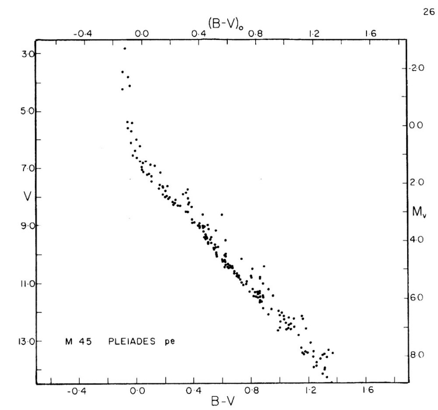

*Atlas of Open Cluster CM Diagrams*, Hagen

# M 41 = NGC 2287



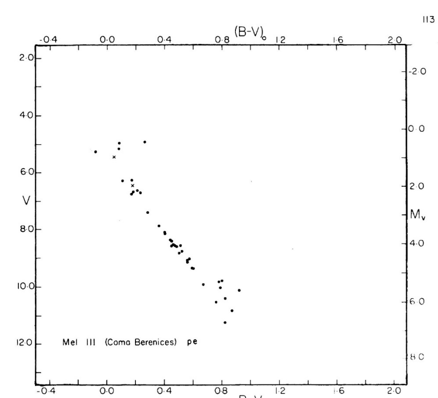

*Atlas of Open Cluster CM Diagrams*, Hagen

# Pleiades



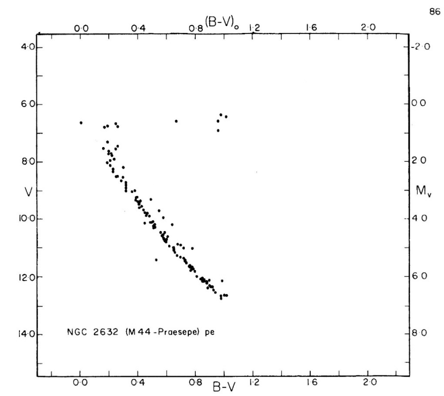

*Atlas of Open Cluster CM Diagrams*, Hagen

# Coma Berenice



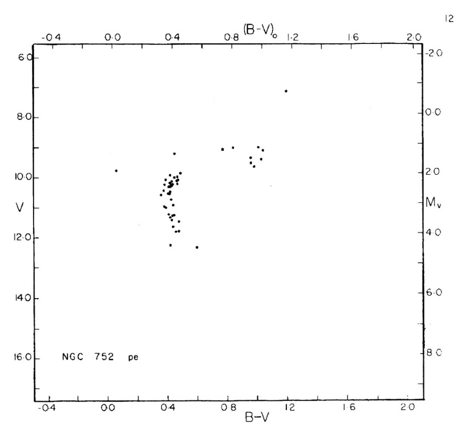

*Atlas of Open Cluster CM Diagrams*, Hagen

# Praesepe



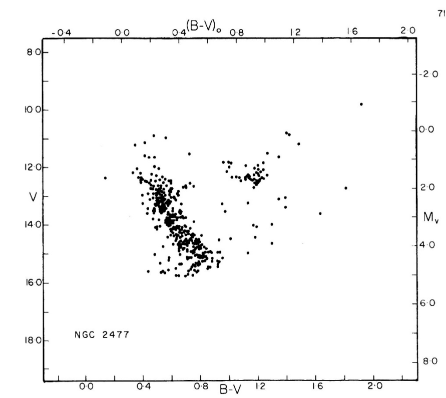

*Atlas of Open Cluster CM Diagrams*, Hagen

# NGC 752



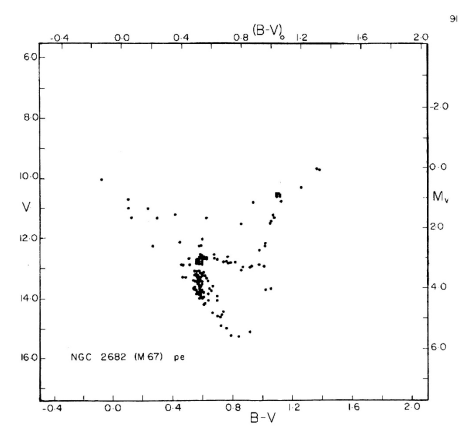

*Atlas of Open Cluster CM Diagrams*, Hagen

# NGC 2477



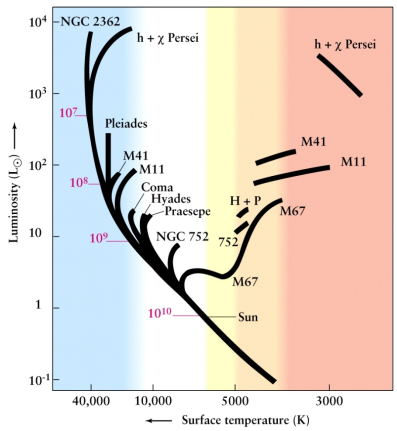

*Atlas of Open Cluster CM Diagrams*, Hagen

# M 67 = NGC 2682




*Atlas of Open Cluster CM Diagrams*, Hagen

# Combined Tracks




*Universe* by Freedman, Geller, and Kaufmann – Adapted from A. Sandage

# PRS Question

1. The main general features that make clusters of stars useful to astronomers are that the stars all have
   a. the same distance from Earth, the same temperature, and joined the cluster at various times
   b. the same apparent magnitude, the same temperature, and the same size
   c. the same intrinsic brightness, differing only in size and temperature
   d. the same distance from Earth, the same age, and the same chemical composition
   e. the same mass and size

# Summary

Star Clusters are Valuable Tools for the Study of Stellar Evolution (birth, life, and death). Just like their individual members, though, clusters also evolve.

Open Clusters are eventually ripped apart by galactic rotation, and all of the stars disperse. The Globular Clusters have sufficient internal gravity to prevent dissipation, but they lack interstellar gas and dust to form a new generation of stars.

The Open Clusters, however, have returned enriched material to the spiral arms of the Galaxy, and with time, there will be a re-birth of stars and the cycle will continue.