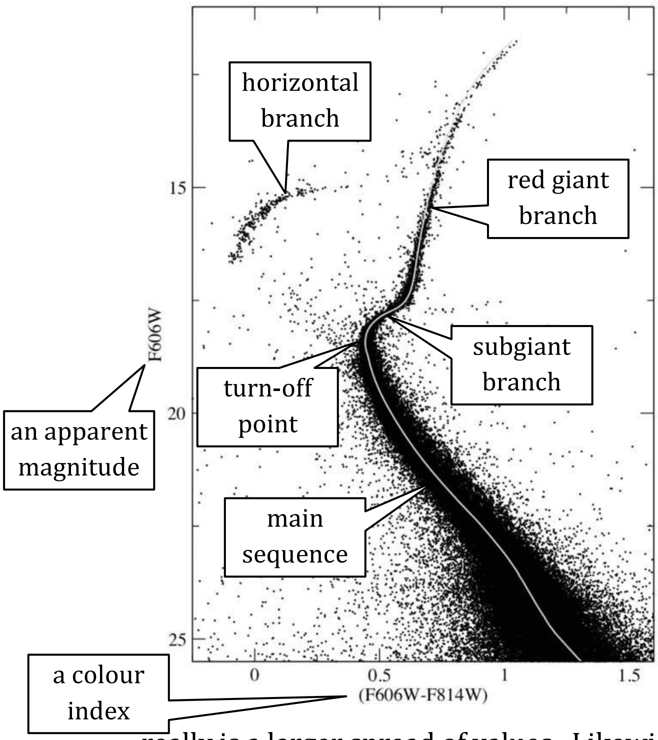
THE HERTZSPRUNG-RUSSELL DIAGRAM

THE AXES

The Hertzsprung-Russell (HR) diagram is a plot of **luminosity** (total power output) against **surface temperature**, both on log scales. Since neither luminosity nor surface temperature is a directly observed quantity, real plots tend to use observable quantities that are related to luminosity and temperature. The table below gives common axis scales you may see in the lectures or in textbooks. Note that the *x*-axis runs from hot to cold, not from cold to hot!

Axis	Theoretical	Observational
x	T_{eff} (on log scale) *or* $\log_{10} T_{\text{eff}}$	Spectral class OBAFGKM *or* Colour index $B - V$, $V - I$
y	$L/L_{\odot}$ (on log scale) *or* $\log_{10}(L/L_{\odot})$	Absolute visual magnitude M_V (or other wavelengths) Apparent visual magnitude V (or other wavelengths)[1]
The symbol $\odot$ means the Sun—i.e., the luminosity is measured in terms of the Sun's luminosity, rather than in watts. T_{eff} is effective temperature (the temperature of a blackbody of the same surface area and total power output).		

BRANCHES OF THE HR DIAGRAM



This is a real HR diagram, of the globular cluster NGC1261, constructed using data from the HST. The line is a fit to the diagram assuming [Fe/H] = −1.35 (the heavy element content of the cluster is 4.5% of the Sun's heavy element content), a distance modulus of 16.15 (the absolute magnitude is found by subtracting 16.15 from the apparent magnitude) and an age of 12.0 Gyr.

Reference: NEQ Paust et al, *AJ* **139** (2010) 476.

Note that the white dwarfs are not visible in this HR diagram, because they are too faint. The magnitude scale of this diagram goes down to apparent magnitude 25, which is absolute magnitude 9 or so—white dwarfs have absolute magnitudes of around 10-15.

Note also that the main sequence gets broader as it gets fainter *because faint stars are harder to measure* (the experimental error is larger), not because there really is a larger spread of values. Likewise, the odd point far from the main branches is a badly measured star or a star that doesn't really belong to the cluster (foreground/background).

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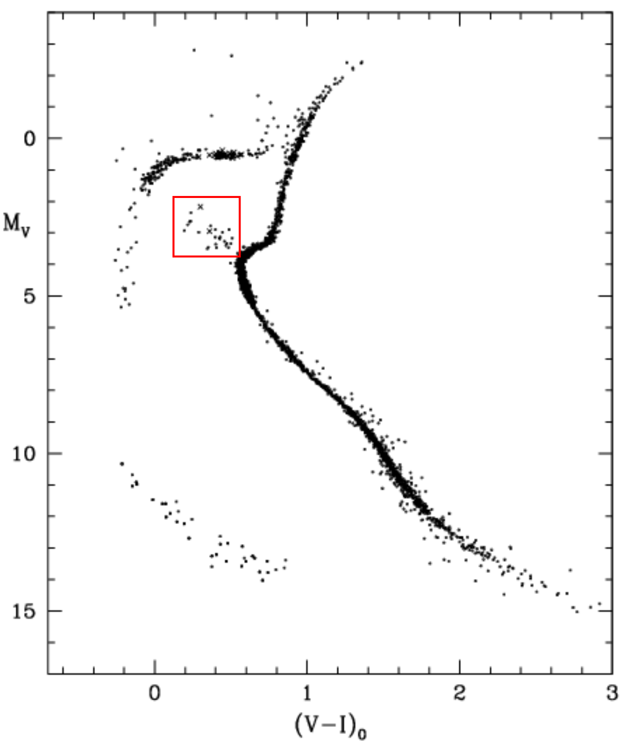
[1] Apparent magnitude can be used ***only*** if all the stars you are plotting are the same distance away (i.e. they are members of the same star cluster or nearby galaxy). If the stars are at different distances, their apparent magnitudes will be affected differently by their individual distances, and so the diagram will not make sense.



This is a "cleaned up" composite HR diagram by WE Harris, combining data from several globular clusters. You should be able to identify the same branches as were visible in NGC1261, plus the white dwarfs at the bottom left (note that most HR diagrams you see will not show the white dwarfs, because—as with NGC1261—they are simply too faint to observe).

Note that there are a few main-sequence stars above the main-sequence turn-off point (in red box). These were also present in NGC1261, but harder to see because of the random foreground stars. These are stars which have gained mass in the past, either by mass transfer in a binary or by coalescence of two stars (in a binary or by accidental collision). They are therefore more massive now than they used to be, and hence have lived longer than a star of their current mass would be expected to (because they were originally lower mass, longer-lived stars). It is usually safe to ignore these stars when you are asked questions about HR diagrams (with the exception that they might sometimes be the bluest—and therefore the hottest—stars on the diagram).

EVOLUTIONARY STAGE OF HR DIAGRAM BRANCHES

The HR diagram branches are correlated with the evolution of the star. Here is a summary of what is going on inside the star in each branch. Note that the greater the mass of the star, the less time it spends in each stage—thus, all the stars in NGC1261 are about 12 Gyr old, even though every branch of the HR diagram is populated.

1	Main sequence	Hydrogen to helium	in central core
2	Subgiant branch	Hydrogen to helium	in thick shell just outside central (helium) core
3	Red giant branch	Hydrogen to helium	in thin shell just outside central (helium) core
4	Horizontal branch	Helium to carbon	in central core
5	Second red giant branch[2]	Helium to carbon	in shell outside central (carbon) core
6	White dwarfs	Nothing	Radiating stored heat

Massive stars that will eventually go supernova do not really populate the branches after the main sequence—they evolve to right and left across the top of the HR diagram, becoming red supergiants in stages 2 and 3, blue or yellow supergiants in stage 4, red again in stage 5, and continuing to change colour (but not brightness, or at least not much) as they go on to fuse heavier elements. Their exact evolutionary path depends on their heavy element content.

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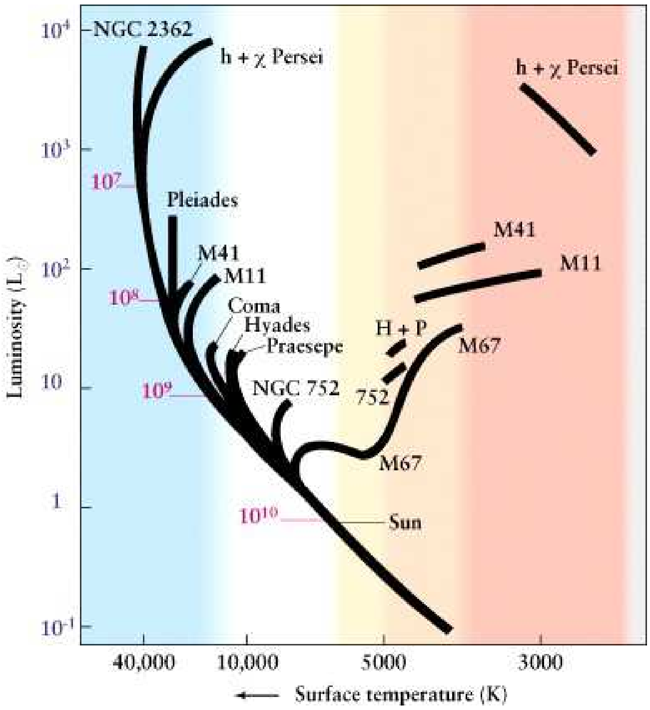
[2] properly known as the *Asymptotic Giant Branch* or AGB. It runs from the right-hand end of the horizontal branch up towards the tip of the red giant branch. It can be seen in both the diagrams, though I haven't labelled it and you don't need to know its proper name.

HR DIAGRAMS OF STAR CLUSTERS

Star clusters are excellent laboratories for studying stellar evolution because:

- their stars are all at the same distance from us (the cluster size is small compared to its distance)—this means that we can construct their HR diagrams from apparent magnitudes, without having to convert to absolute magnitudes;
- their stars are all the same age, to within a few million years (clusters form from a single large gas cloud which fragments as it collapses under its own gravity);
- their stars all have the same initial chemical composition.

THE HR DIAGRAM AND THE CLUSTER AGE



The age of a cluster is given by the *main sequence turn-off point*—the highest point on the main sequence that is still populated by stars. On the left is a well-known schematic diagram combining the HR diagrams of star clusters of different ages: NGC2362 is the youngest and M67 the oldest. The pink numbers give the main sequence lifetime in years for stars at that point in the main sequence—e.g. our Sun has a main sequence lifetime of 10 Gyr. From this we see that the "double cluster" h and χ Persei has an age of $<10^7$ years (its turn-off point is above the 10^7 year label), the Pleiades about 10^8 years, the Hyades and Praesepe roughly 10^9 years, and M67 perhaps 4×10^9 years.

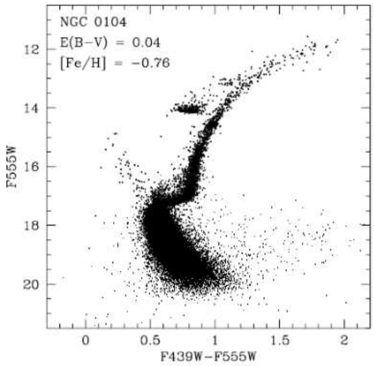
Note that the older the cluster is, the fainter its faintest red giants are: h and χ Persei does have red giants, but they are red supergiants with luminosities several thousand times that of the Sun, whereas the Hyades and Praesepe have red giants with luminosities only a few tens of times greater than the Sun's. Also note that the shape of M67's red giant branch is different from that of younger clusters—it has a subgiant branch, and its red giant branch is longer and more continuous. This is because lower-mass stars evolve to the giant branch more gradually than high-mass stars, so we can catch them during the transition.

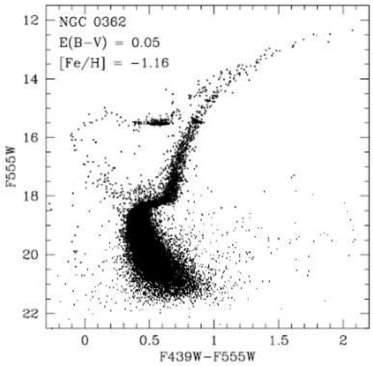
The turn-off point determines the age because *massive main-sequence stars are brighter and have shorter lives than less massive main-sequence stars*. We do **not** determine this by studying clusters—that would be a circular argument—but by constructing the *mass-luminosity relation* for main-sequence binary stars. Binary stars are the only stars whose mass we can actually measure (because we can use the stars' orbits to determine the gravitational forces that are acting).

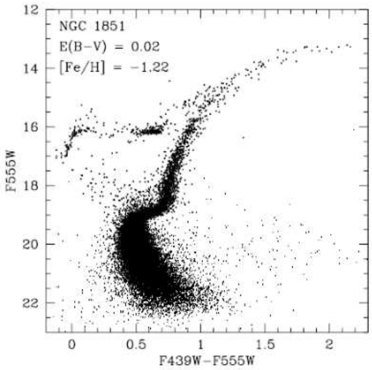
The HR Diagram and the Cluster Heavy Element Content

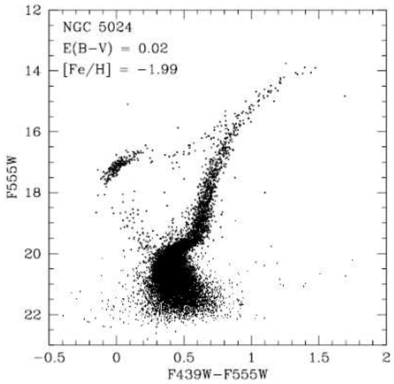
Heavy elements are much better at absorbing light than hydrogen and helium, because they have more electrons and more energy levels. Therefore the heavy element content affects the interior structure of the star, and hence its position on the HR diagram. The usual effect is that stars with lower heavy element content have bluer colours than stars higher in heavy elements (the star is smaller and more compact, because electromagnetic energy escapes more easily, and therefore—since its total power output is unaffected—its surface is hotter).

Professional astronomers use computer codes to fit the heavy-element content of the cluster, along with its age and distance—the output of one such code is seen on the HR diagram of NGC1261. However, there is one place where the effect of the heavy-element content is obvious without detailed fits: the shape of the horizontal branch.









This series of four globular cluster diagrams from G Piotto et al., *A&A* **391** (2002) 945 shows what happens to the horizontal branch as the heavy element content is reduced (shown by the value of [Fe/H] becoming more negative). The HB starts out as a short stub just to the left of the RGB and gradually extends outwards, until in the cluster with lowest heavy element content (1% of the Sun's, or 0.02% by mass) most of the HB stars are blue. (These diagrams are in terms of *apparent* magnitude, so the difference in the *y*-axis scale just reflects the different distances of the clusters. The HST apparent magnitudes F439W and F555W correspond to blue light and yellow-green light respectively—they are similar to the usual *B* and *V* ("blue" and "visual") apparent magnitudes.)

By comparing these diagrams with the NGC1261 diagram and the composite diagram, you will see that both NGC1261 and the composite are systems low in heavy elements—they have long horizontal branches extending out to the blue[3].

In clusters with heavy-element content similar to the Sun's, the horizontal branch moves so far to the red that it lies practically on top of the red giant branch. It is then called the *red clump*. Individual red clump stars are hard to tell from red giant stars, as they have similar colour and

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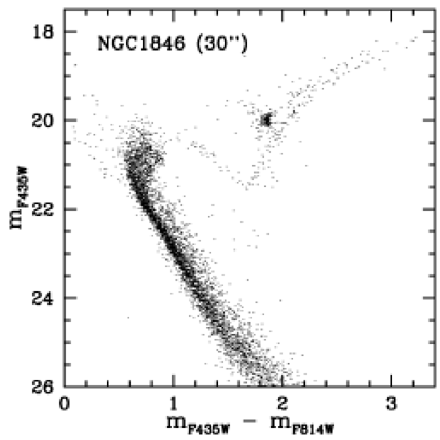
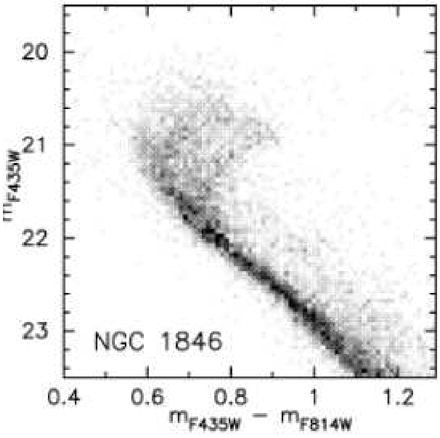
[3] In fact, horizontal-branch morphology is a bit more complicated than this—some clusters with similar heavy-element content have differently shaped HBs. This so-called *second parameter effect* is mostly due to age, but other parameters such as helium abundance also seem to contribute.

power output, but in terms of stellar evolution they are not the same—red giant stars are fusing hydrogen to helium in a shell around an inert helium core, whereas red clump stars are fusing helium to carbon inside the core.





The HR diagram to the left is for a cluster in the Large Magellanic Cloud with a heavy-element content somewhat lower than the Sun's, but higher than that of most globular clusters. The red giant branch contains rather few stars, but just about visible. The stars in the red clump are *just* to the left of the RGB in this cluster—they would be even further to the right in a cluster of solar metallicity.

You might notice that the turn-off point for this cluster is not as sharp as in the previous diagrams. A close-up of this region (below left) shows that in fact there are two separate turn-off points, one slightly below the other. This means that, unusually for a cluster, NGC1846 has two stellar populations of slightly different age—Mackey et al., the authors of the paper I took these diagrams from[4], estimate that the age difference is about 300 Myr (the older population, with the lower turn-off, is 1.9 Gyr old, and the younger 1.6, from fits of the HR diagram to stellar evolution models).

These are HST measurements, as with Piotto et al., but the colour index is made using F814W (a red/near infra-red magnitude) instead of F555W. This is why the *x*-axis scale of these plots is different from those on the previous page. Notice that the turn-off point is only about half a magnitude fainter than the red clump, whereas in the globular clusters it was about 2 magnitudes fainter—this is because NGC1846 is much younger than a typical globular cluster.

THE HR DIAGRAM OF NEARBY STARS

This is very important, because the distances (and hence the absolute magnitudes) of nearby stars can be determined using parallax. Therefore, the HR diagram of nearby stars uses absolute magnitudes, instead of apparent magnitudes as with star clusters. Comparing the main sequence of a star cluster with our known local main sequence allows us to determine the distance of the cluster—for example, if the main sequence of the cluster (in terms of apparent magnitude) were 5 magnitudes fainter than the local main sequence (in terms of absolute magnitude), we would know that the cluster was 10 times further away than the reference distance for absolute magnitude (which is 10 parsecs, or 32.6 light-years—so the cluster would be 100 parsecs away).

The plot on the next page shows the local HR diagram as measured by the Hipparcos satellite. It includes 20853 stars with accurately measured parallax (precision of parallax, and therefore of

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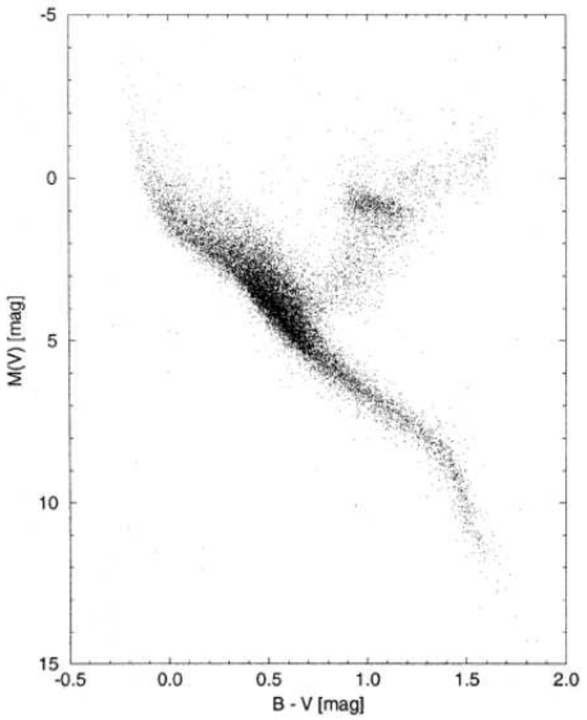
[4] AD Mackey et al., *ApJ* **681** (2008) L17.

distance, better than 10%) and colour index (precision of colour index better than ±0.025 magnitudes).[5]



The main sequence, red giant branch and red clump can be clearly seen on this HR diagram. The white dwarf branch is not visible—Hipparcos was a small satellite with a small telescope, and could not see many white dwarfs. The few it could see were not measured precisely enough to be included in this diagram. For the same reason, the lower end of the main sequence, below about magnitude 6, fades out as it gets fainter, even though in fact fainter stars are more common (as we know from samples that count every star within a certain distance): it's not that the faint stars are not there, it's that the faint stars were not visible, or not measurable with sufficient precision, with Hipparcos' telescope.

The significant features of the Hipparcos HR diagram are:

- The main sequence extends up to magnitudes less than 0 (corresponding to stars at least 100 times brighter than the Sun). These stars have short main-sequence lifetimes (a star 100 times brighter than the Sun would be roughly four times as massive as the Sun, and would have a main-sequence lifetime of about 400 million years). Therefore these stars are much younger than the Sun (which we know from radioactive dating is about 4.6 Gyr old).
- On the other hand, there are some quite faint red giants: the red giant branch starts in the middle of the diagram with stars that are not much brighter than the Sun (recall that the Sun's absolute magnitude is about 4.8). These stars must be at least as old as the Sun, and could easily be older. (Compare this with the line for M67 on the diagram on page 3.)
- There is a clear red clump at about $M_V = +1$ and $B - V = 1.0$ to 1.2. This shows that the stars near the Sun are—like the Sun itself—comparatively high in heavy elements (otherwise this would be a horizontal branch instead of a red clump).

We conclude that *the stars in the solar neighbourhood are not all the same age*. Some are at least as old as the Sun, while others are a factor of 10 younger. This shows that star formation in the Milky Way is a continuing process—the stars in the Galaxy didn't all form at the same time.

The main sequence in the middle of the plot, where we have the largest number of stars, is quite broad—much wider than the error on the colour measurement (which is <0.025 magnitudes, remember). This is a real spread, and is mostly due to the fact that these stars have different ages—main sequence stars do not move up or down the sequence as they age, but they do move across it from left to right, getting slightly cooler but brighter (therefore larger) as they get older. There may also be some effect from differences in chemical composition—stars lower in

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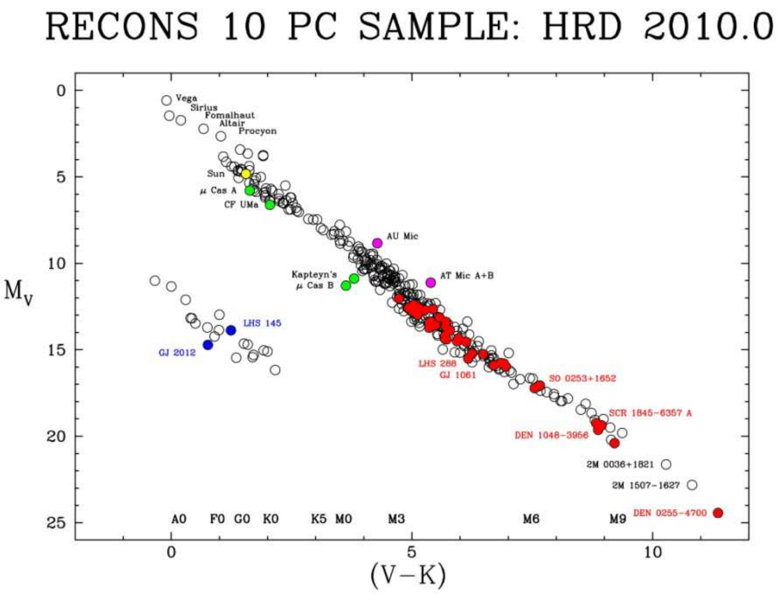
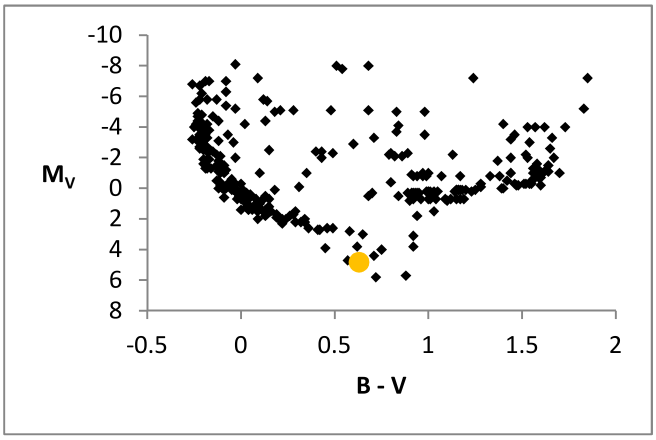
[5] MAC Perryman et al, *A&A* **323** (1997) L49

heavy elements tend to be bluer on the main sequence, though not as much as they are on the horizontal branch—but we can see from the lack of a long horizontal branch that there are not many low-metallicity stars near the Sun.

To get a better idea of how common different types of stars are, we can look at a *distance-limited sample*, i.e. the set of stars closer than some set distance. This is a fair and representative sample—stars are not more likely to be included if they are intrinsically bright, as is the case with the Hipparcos sample.



The HR diagram on the left is from the RECONS project (www.recons.org), which aims to construct a complete list of the stars within 10 pc of the Sun. The Sun is the yellow point, and the red and blue points are stars whose parallaxes the RECONS team has determined for the first time. Green points are stars low in heavy elements (note that they are a bit bluer than normal stars), and the magenta points are the three components of a very young system which has not quite settled on to the main sequence yet. Notice that the Sun is very close to the top of this HR diagram—only about 15 stars are brighter, and hence presumably more massive, out of a sample of 376—and there are no red giants, and no main-sequence stars of O or B spectral class. This tells us that these stars are rare, accounting for <1% of the stars near the Sun.



In contrast, the HR diagram of the 314 brightest stars in the night sky[6] shows that most of these are either main-sequence stars brighter and hotter than the Sun (which is shown by the yellow dot) or red giants. There are even some supergiants with absolute magnitudes of around −7. A few bright stars appear bright because they are very nearby (for example α Cen B, a K class main-sequence star with $B - V = 0.88$ and $M_V = 5.7$), but the vast majority appear bright because they really are bright—they are very luminous stars several hundred light years away. There is very little overlap between this sample and the RECONS sample: most nearby stars are actually too faint to see with the naked eye.

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[6] Data from Garrison and Beattie, http://www.astro.utoronto.ca/~garrison/oh.html

This sample is *magnitude limited* (in fact it contains all the stars with apparent visual magnitude brighter than 3.55). It is obviously *not* a fair and representative sample of stars in the disc of the Milky Way! When looking at HR diagrams you should remember that in fact *all* samples are magnitude limited, because a sufficiently faint star will always be invisible—even the RECONS sample is certainly missing some, perhaps many, brown dwarfs with absolute magnitudes >20. Therefore, when interpreting HR diagrams, you should always be careful about drawing conclusions from the apparent absence of faint objects such as white dwarfs and very low mass main-sequence stars: the chances are that these objects are there, but do not appear on the diagram because they are too faint for the telescope to pick up.

SUMMARY

1. The Hertzsprung-Russell diagram is a plot of *log*(*luminosity*) (usually expressed as absolute or, for clusters *only*, apparent magnitude) against *log*(*surface temperature*) (usually expressed as a colour index, sometimes—especially in old plots—as spectral class), with luminosity decreasing from the top of the plot to the bottom and temperature decreasing from left to right. Note that *large* magnitudes correspond to *small* luminosities.
2. Stars on the HR diagram are concentrated in a small number of well-defined regions or *branches*, corresponding to different evolutionary stages. The main branches are the main sequence, the red giant branch, the horizontal branch and the white dwarfs (which are often not present on diagrams of real data, because they are too faint to observe).
3. The *age* of a star cluster is determined by the *main sequence turn-off point*: the further up towards the top left the main sequence extends, the younger the cluster. Another indicator is the *length of the red giant branch*: fainter red giants indicate older clusters (it means that fainter, lower-mass stars have evolved on to the RGB).
4. The *heavy element content* or *metallicity* of a cluster is determined by the *length of the horizontal branch*: a long horizontal branch extending out to the blue indicates very low heavy element content, while a *red clump* sitting on top of the lower red giant branch indicates approximately solar (i.e. high) heavy element content.
5. The presence of *both* bright main sequence stars *and* faint red giants in the HR diagram of (relatively) nearby stars indicates that these stars span a wide range of ages, from much younger than the Sun up to at least as old as, and probably older than, the Sun.
6. Magnitude-limited samples (which means *all* samples, to a greater or lesser degree) will systematically undercount or omit faint objects, especially white dwarfs and the bottom end of the main sequence. If you do not see white dwarfs on an HR diagram (which you usually won't), you should ***not*** assume that they are not present in the object being diagrammed.

You should now try the "Hertzsprung-Russell Diagram Self Test" questions
(see separate document).